Multi-Life Cycle Assessment of Floor Systems

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I.F. (Furkan) Güven

TU Delft

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by

I.F. (Furkan) Güven

Student Name	Student Number
I. F. Güven	4654978

Project duration: April 3, 2024 – January 6, 2024
Thesis committee: Dr. F. (Florentia) Kavoura, TU Delft, Chair
Dr. O. (Oğuzhan) Çopuroğlu, TU Delft
MSc Y. (Yufei) Zhang, TU Delft, Supervisor

	Department	Section
Dr. F. (Florentia) Kavoura	Engineering Structures	Steel and Composite Structures
Dr. O. (Oğuzhan) Çopuroğlu	3MD	Materials and Environment
MSc Y. (Yufei) Zhang	Engineering Structures	Steel and Composite Structures

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Preface

This thesis represents the completion of my journey toward earning a Master of Science degree in Civil Engineering at Delft University of Technology. Throughout this process, I have had the opportunity to explore a topic that combines my academic interests with practical engineering challenges, enriching my knowledge and fostering my growth as an engineer and researcher.

I would like to express my sincere gratitude to my graduation committee for their invaluable feedback and support throughout this project. In particular, I am deeply grateful to Yufei Zhang, whose guidance significantly enhanced the quality of this research. I am also profoundly thankful to Dr. Florentia Kavoura for her unwavering support and constructive feedback throughout the thesis. Additionally, I extend my heartfelt appreciation to Dr. Oğuzhan Çopuroğlu for his insightful guidance and critical expertise, which provided valuable direction and clarity during key stages of this research. Their combined mentorship has been vital in shaping this work and guiding me through the challenges of this journey.

Finally, I wish to thank my family and friends for their unwavering support and encouragement throughout this process. Your belief in me has been a constant source of motivation and inspiration.

I hope this thesis contributes meaningfully to the field of Structural Engineering and provides insights that will support further advancements in engineering practices. Completing this work has been both a challenging and rewarding experience, and I look forward to applying the knowledge and skills gained as I move forward in my career.

I.F. (Furkan) Güven
Delft, January 2025

Abstract

The construction industry significantly contributes to global greenhouse gas emissions, underscoring the need for sustainable building practices. Floor systems, which comprise 68% [1] of building materials, are critical in determining environmental performance. Despite their importance, comprehensive Multi-Life Cycle Assessment (MLCA) of floor systems in the Dutch context are scarce. Given the importance of these considerations, this study addresses the following research question:

"What are the structural and sustainability performance characteristics of different floor systems used in buildings in the Netherlands when evaluated using a Multi-Life Cycle Assessment (MLCA)?"

To address this main research question, a systematic MLCA framework was developed, integrating structural and environmental performance evaluations. This framework was applied to evaluate three commonly used floor systems: cast-in-situ concrete slabs, hollow core slabs, and deep deck composite slabs. The methodology included parametrizing the design of these floor systems using Excel and Grasshopper, designing slabs for comparable load-bearing capacities, assessing environmental impacts using the Nationale Milieu Database (NMD) and GPR Materiaal, and accounting for degradation factors such as reinforcement corrosion and concrete strength reduction.

By applying the outlined methodology, the key findings of this study were identified and are explained in this report, including:

- Adopting a circular building economy approach significantly reduces environmental impacts. For example, the prefabricated hollow core slab and deep deck composite slab reduced the Environmental Cost Indicator (ECI) by 78.06% and 87.10%, respectively, compared to the cast-in-situ concrete slab. These results highlight the advantages of material reuse and improved efficiency.
- The deep deck composite slab consistently achieved the lowest environmental impacts across categories, requiring no additional interventions over three life cycles. In comparison, the hollow core slab performed well but incurred higher impacts due to the environmental burden of strengthening measures.
- When evaluating performance across multiple life cycles, it is essential to consider long-term factors such as material degradation. This study found that reinforcement corrosion in the hollow core slab necessitated interventions, demonstrating the impact of degradation mechanisms on structural integrity and environmental outcomes.
- While reuse feasibility shows promise, its scalability relies on robust inventory management, standardized material passports, and design-for-disassembly practices. These steps are critical to overcoming current barriers and realizing widespread adoption of circular construction principles.

This research provides a robust MLCA framework and highlights the benefits of circular construction principles, offering valuable insights for sustainable floor system design and reuse strategies in the construction industry.

Contents

List of Figures

List of Tables

Nomenclature

Abbreviations

Abbreviation	Definition
ADP	Abiotic Depletion Potential
AP	Acidification Potential
AM	Analytical Model
BM	Bending Moment
Cat	Category
CE	Circular (Building) Economy
CLT	Cross-Laminated Timber
Defl	Deflection
ECI	Environmental Cost Indicator
EP	Eutrophication Potential
ETP	Eco-toxicity Potential
FAETP	Freshwater Aquatic Ecotoxicity Potential
FE	Finite Element
GHG	Greenhouse Gas
GPR	Gemeente Praktijk Richtlijn Gebouw
GWP	Global Warming Potential
HTP	Human Toxicity Potential
IRP	Ionizing Radiation Potential
ISO	International Organization for Standardization
LC	Life Cycle
LCA	Life Cycle Assessment
LE	Linear (Building) Economy
MAETP	Marine Aquatic Ecotoxicity Potential
MLCA	Multi-Life Cycle Assessment
MPG	Milieuprestatie Gebouwen
NM	Numerical Model
NMD	Nationale Milieu Database
ODP	Ozone Layer Depletion Potential
PEF	Product Environmental Footprint
PNA	Plastic Neutral Axis
POCP	Photochemical Oxidation Potential
PM	Particular Matter Emissions
RC	Reinforced Concrete
SF	Shear Force
SLS	Serviceability Limit State
SQP	Soil Quality Index Potential
TETP	Terrestrial Ecotoxicity Potential
UC	Unity Check
ULS	Ultimate Limit State
WDP	Water Depletion Potential

Symbols

Symbol	Definition	Unit
A_a	Cross-sectional area of the structural steel section	[mm^2]
A_c	Cross-sectional area of concrete	[mm^2]
$A_{c,tr}$	Transformed cross-sectional area of concrete	[mm^2]
A_p	Cross-sectional area of profiled steel sheeting	[mm^2]
$A_{remaining}$	Effective remaining reinforcement area due to corrosion	[mm^2]
A_s	Cross-sectional area of reinforcement	[mm^2]
A_{sl}	Area of the tensile reinforcement	[mm^2]
b	Width	[mm]
b_{eff}	Effective width	[mm]
b_w	Width of the cross-section at the centroidal axis	[mm]
c	Concrete cover thickness	[mm]
d	Effective depth of a cross-section; diameter	[mm]
d_r	Diameter reinforcement	[mm]
d_t	Diameter of tendon	[mm]
$d_{remaining}$	Effective remaining reinforcement diameter due to corrosion	[mm]
D	Carbonation depth	[mm]
E_a	Modulus of elasticity of structural steel	[MPa]
E_c	Modulus of elasticity of concrete	[MPa]
E_{cm}	Secant modulus of elasticity of concrete	[MPa]
E_s	Modulus of elasticity of steel	[MPa]
EI_0	Flexural stiffness	[kNm^2]
EI_{eff}	Effective flexural stiffness	[kNm^2]
f_p	Tensile strength of prestressing steel	[MPa]
f_{pk}	Characteristic tensile strength of prestressing steel	[MPa]
f_{ck}	Characteristic compressive cylinder strength of concrete at 28 days	[MPa]
f_{cm}	Mean value of concrete cylinder compressive strength	[MPa]
f_{cd}	Design value of concrete compressive strength	[MPa]
f_{yk}	Characteristic yield strength of reinforcement	[MPa]
f_{yd}	Design yield strength of reinforcement	[MPa]
f_{sk}	Characteristic strength of steel reinforcement	[MPa]
f_{sd}	Design strength of steel reinforcement	[MPa]
F_c	Concrete force	[kN]
F_p	Prestress tendon force	[kN]
F_s	Reinforcement steel force	[kN]
F_{gov}	Governing force	[kN]
h	Height; depth; thickness	[mm]
h_a	Height of the steel section	[mm]
h_c	Depth of the concrete	[mm]
h_p	Overall depth of the profiled steel sheeting	[mm]
h_w	Height of the steel web	[mm]
i_{corr}	Corrosion current density	[$\mu A\,cm^{-2}$]
I	Second moment of inertia	[mm^4]
I_a	Second moment of area of the steel section	[mm^4]
I_c	Second moment of area of concrete	[mm^4]
I_p	Second moment of area of plate	[mm^4]
k	Empirical factor for design shear resistance	[-]
L	Span length between two supports	[mm]
M_{Ed}	Design value of the applied internal bending moment	[kNm]

Symbol	Definition	Unit
M_d	Design bending moment	[kNm]
M_{Rd}	Design value of the resistance bending moment	[kNm]
n	Modular ratio	[-]
n_{bottom}	Number of tendons at the bottom	[-]
n_{top}	Number of tendons at the top	[-]
p	Corrosion penetration	[mm]
q_d	Design value distributed load	[kN/m]
R	Reaction forces	[kN]
r	Radius	[mm]
s	Spacing of the reinforcement	[mm]
t	Time	[years]
t_p	Thickness of the plate	[mm]
t_f	Thickness of a flange of the structural steel section	[mm]
t_w	Thickness of the web of the structural steel section	[mm]
v	Strength reduction factor for concrete cracked in shear	[-]
v_{Ed}	Design longitudinal shear stress	[MPa]
V_{corr}	Corrosion rate	[mm/year]
V_{Ed}	Effective design shear force	[kN]
$V_{pl,Rd}$	Design value of the plastic resistance of the composite section to vertical shear	[kN]
V_{Rd}	Resistance design shear force	[kN]
$V_{Rd,c}$	Design shear resistance of the member without shear reinforcement	[kN]
$V_{Rd,max}$	Design value of the maximum shear force, limited by crushing	[kN]
$V_{Rd,s}$	Design value of the shear force sustained by shear reinforcement	[kN]
x	Distance between PNA and the top of the slab	[mm]
α	Characterization factor	[-]
δ	Deflection	[mm]
δ_{max}	Maximum allowed deflection	[mm]
γ_c	Material Factor Concrete	[-]
γ_p	Material Factor prestressed steel	[-]
γ_s	Material Factor Steel	[-]
ρ	Density	[kg/m^3]
σ_{bot}	Stress at the bottom of the slab	[MPa]
σ_{cp}	Concrete compressive stress at centroidal axis	[MPa]
σ_{top}	Stress at the top of the slab	[MPa]

1
Introduction

Chapter 1 provides an overview of the research context, problem, objectives, scope, and questions. It also outlines the theoretical framework and methods, and concludes with a summary of the thesis structure.

1.1. Research Context

In the construction industry, sustainability is becoming increasingly crucial. Floor systems, which account for approximately 68% [1] of the materials used in a building's structure (see Figure 1.1), significantly influence the overall sustainability performance of structures. The design and selection of floor systems involves balancing material use, environmental impact, cost, and structural performance.

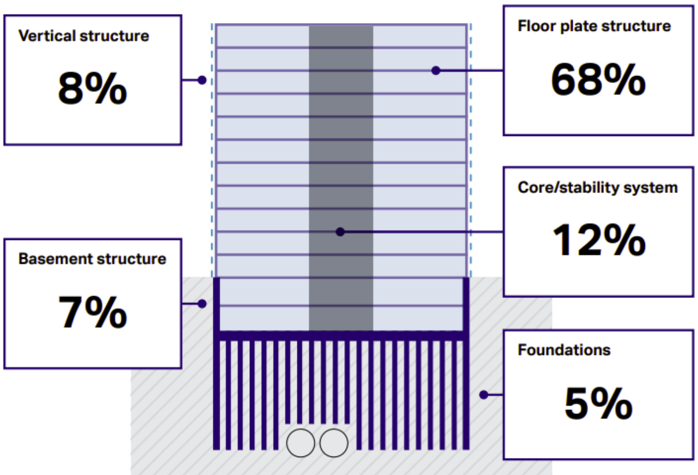


Figure 1.1: Structural Building Component Breakdown [1]

Buildings are major contributors to global greenhouse gas (GHG) emissions, accounting for about 21% of the total worldwide [1]. Recognizing this, the Dutch government aims to reduce carbon emissions by 55% from 1990 levels by 2030, highlighting the need for sustainable construction practices [2]. This research explores whether the broader adoption of composite floor systems can significantly decrease material usage and environmental footprints, contributing towards the European Union's goal of achieving carbon neutrality by 2050 [3].

Evaluating alternative floor systems, such as reinforced concrete, hollow core, and composite slabs, is essential to determine the most sustainable design solutions that meet structural demands.

1.2. Research Problem

Despite the critical importance of floor systems in building construction, comprehensive analyses that evaluate their sustainability across multiple life cycles are notably lacking, especially within the context of the Netherlands. Many studies focus on the environmental impacts of these systems for a single or perhaps two life cycles, but comprehensive assessments covering multiple life cycles are rare.

This limitation becomes increasingly significant as the construction industry advances towards sustainable and circular economy practices, which prioritize the reuse of materials. Additionally, with the approaching introduction of Set A2 environmental impact categories in the Netherlands (an expanded set of 19 categories that builds on the existing 11 categories under Set A1; see Section 2.6 for details), there is an urgent need for up-to-date research to adapt and incorporate these new standards.

The lack of a systematic framework that integrates the multiple life cycles of floor systems, alongside potential degradation factors such as concrete strength reduction and steel reinforcement corrosion, complicates the ability to fully understand and evaluate the long-term sustainability and structural integrity of reused floor systems. This shortcoming restricts the ability of industry stakeholders to make informed decisions that align with future sustainability goals.

This research aims to bridge these gaps by providing a comprehensive assessment that not only evaluates the environmental impacts of various floor systems within the Dutch context but also considers their performance across multiple life cycles (specifically three in this study), incorporating both the existing categories (Set A1) and the upcoming categories (Set A2).

1.3. Research Objectives

This research project aims to contribute to the existing literature by conducting a multi-life cycle assessment of the sustainability of floor systems. Specifically, the objectives are to:

1. Identify and select floor systems and design configurations to minimize environmental impact while meeting structural requirements.
2. Quantify the environmental indicators considered for multi-LCA of concrete-based floor systems by conducting a detailed analysis of key parameters such as global warming potential, ozone layer deletion potential, and the environmental cost indicator throughout the life cycle stages.
3. Develop a comprehensive framework for analysing trade-offs in selecting and designing floor systems, integration of factors such as material use, environmental impact, and structural performance will be conducted.

1.4. Research Scope

This study evaluates various floor systems in steel framed buildings:

1. Cast in-situ concrete slab
2. Hollow core slab
3. Deep Deck composite slab

This study evaluates various floor systems in steel-framed buildings, including cast in-situ concrete slabs, hollow core slabs, and deep deck composite slabs. It focuses on the most common concrete-based floor systems used in the Netherlands and Europe, exploring both traditional and alternative options like prefabricated and composite solutions. The research aims to understand the benefits and environmental impacts of these systems to offer insights into sustainable and efficient floor system design in contemporary construction practices.

The selection of floor systems in this study is guided by trends in research publications, as shown in Figure 1.2. The figure highlights that cast in-situ concrete slabs, hollow core slabs, and deep deck composite slabs are frequently studied in the Netherlands, indicating their relevance for evaluating performance within the context of sustainable construction.

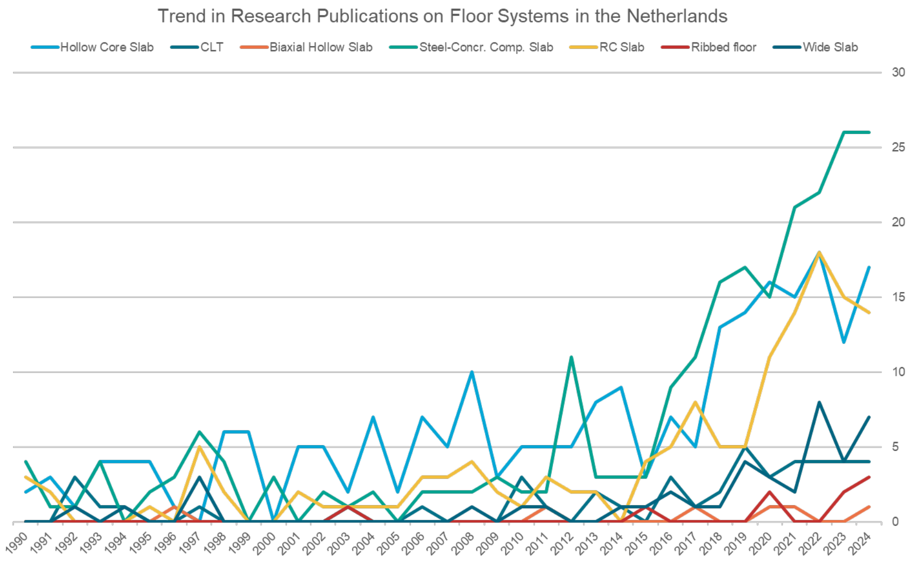


Figure 1.2: Trend in Research Publications on Floor Systems in the Netherlands [4]

1.5. Research Questions

This thesis aims to evaluate the environmental sustainability of various floor systems used in buildings across the Netherlands through a comprehensive Multi-Life Cycle Assessment (MLCA). The research questions are structured to guide the exploration of structural and environmental performances across multiple life cycles, with specific emphasis on assessing and comparing the impacts of different systems.

Main Research Question:

What are the structural and sustainability performance characteristics of different floor systems used in buildings in the Netherlands when evaluated using a Multi-Life Cycle Assessment (MLCA)?

Sub-questions:

1. Which floor systems can be selected for analysis based on the most common floor types for buildings in the Netherlands?
2. What are the performance characteristics of each floor system for steel-based buildings in terms of material use, strength, and stiffness?
3. What factors need to be considered in a Multi-Life Cycle Assessment of different floor systems?
4. What are the differences in environmental impact outcomes among the different floor systems?
5. How can a framework be developed for assessing the environmental impact over multiple life cycles of different floor systems?

1.6. Research Method

This study evaluates the environmental and structural impacts of three different types of floor systems in steel-framed buildings, spanning three life cycles. The floor systems analyzed include cast-in-situ concrete slabs, hollow core slabs, and deep deck composite slabs. All systems are designed to meet the same bending moment unity checks to ensure comparability in structural performance across the different systems and life cycles.

The environmental impact assessment is conducted using a Life Cycle Assessment (LCA) based on the cut-off method. This method allocates environmental impacts to their corresponding life cycle stages, utilizing a comprehensive material inventory that includes concrete, steel, and other building components. A functional unit of one square meter of floor area is used to standardize the comparison across different systems. The data for the LCA is sourced from the Nationale Milieu Database (NMD), which provides verified environmental data in line with the Dutch Building Decree. The LCA tool employed, GPR Materiaal, is chosen for its compliance with ISO 14040 and ISO 14044 standards and its integration with the NMD, ensuring reliable and up-to-date assessments.

Each life cycle involves structural checks to address the reductions in compressive strength and the corrosion by carbonation of steel reinforcement, which are natural degradation effects over time. If the systems meet Eurocode standards for structural integrity without additional interventions, no extra environmental impact is attributed to that cycle. However, if the systems fail to meet these standards, steel plate bonding is used as an intervention technique. This method involves attaching steel plates to the tension zone of the slabs to restore their load-bearing capacity and compensate for the diminished material properties. The environmental impacts of these interventions are included in the LCA.

This comprehensive methodological approach allows for a detailed understanding of how different floor systems perform both structurally and environmentally across multiple life cycles.

1.7. Research Structure

This section delineates the structure of the thesis, illustrating how the research objectives and questions are systematically addressed throughout the document. Each chapter is purposefully designed to contribute towards achieving the objectives specified in Section 1.3 and to address the research questions detailed in Section 1.5.

- **Chapter 1 - Introduction:** This initial chapter sets the stage by outlining the research context, problem, objectives, and questions.
- **Chapter 2 - Literature Review:** This chapter reviews existing literature on various floor systems, focusing on structural and environmental aspects. It explores sustainability assessment methods, identifies the research gap, and details various intervention techniques.
- **Chapter 3 - Design of Floor Systems:** This chapter discusses the methodology for comparing different floor systems, focusing on cast in-situ concrete slabs, prefabricated hollow core slabs, and deep deck composite slabs. It covers design parameters, material quantities, and the effects of specific degradation factors such as corrosion and strength reduction.
- **Chapter 4 - Parametric Model:** Describes the development and application of a parametric model used for the structural analysis of slabs, including setup, material assignment, load applications, and the presentation of numerical results.
- **Chapter 5 - Multi-Life Cycle Environmental Impact Analysis:** This chapter integrates the methodology and results of the environmental impact assessment. It begins by outlining the framework for multi-life cycle environmental analysis, detailing the selection of impact categories, the application of the shadow pricing method, and how different life cycles can be incorporated. Following this methodological overview, it describes the assessment approach used in this study and presents the Life Cycle Assessment (LCA) results for each slab, highlighting key environmental performance indicators and comparing the impacts across multiple life cycles.
- **Chapter 6 - Results and Analysis:** Provides a detailed analysis of environmental impact results, addressing impacts across single and multiple life cycles, and discusses the implications of intervention measures and degradation factors.
- **Chapter 7 - Discussion and Conclusion:** Concludes the thesis by answering the research subquestions and the main question. It reflects on the limitations of the study and suggests areas for further research.

Appendices and Supplementary Materials: The thesis includes detailed appendices covering analytical approaches for each slab type, environmental impact result graphs, and additional calculations that substantiate the research findings.

This structure provides comprehensive coverage of the topic, facilitating a thorough exploration of the sustainability of floor systems within a multi-life cycle context.

2
Literature Review

This chapter reviews the existing literature relevant to the environmental impact assessment of concrete-based floor systems in the Netherlands. It explores various floor systems, degradation mechanisms affecting their durability, intervention techniques for extending their service life, allocation methods in life cycle assessments, and environmental impact categories used in sustainability evaluations. By examining these areas, the chapter establishes the necessary foundation to address the gaps in understanding the long-term environmental performance and structural integrity of floor systems over multiple life cycles.

2.1. Floor Systems in the Netherland

Selecting the appropriate floor system is crucial in building construction as it directly influences structural integrity, sustainability, construction efficiency, and overall building performance.

This chapter examines the most commonly used floor systems, providing descriptions and insights into their prevalence.

In the Netherlands (and throughout Europe), each of these floor systems must comply with the relevant Eurocodes. The applicable design references are as follows:

- Cast-in-Situ Concrete Floors are designed in accordance with EN 1992 (Eurocode 2) [5] for concrete structures, addressing bending, shear, deflection, and fire resistance checks.
- Hollow Core Slabs follow EN 1992 [5] (for general concrete design) and also EN 1168 [6], which is a specific product standard for precast hollow core elements. In addition, manufacturers such as Bruil [7], VBI [8], Dycore [9] and Preco [10] offer product brochures that detail recommended design practices and installation methods for their proprietary systems.
- Biaxial Hollow Slabs, Ribbed Floors, and Wide Slabs also rely on EN 1992 [5] for design principles, with supplementary guidance available in precast-specific product standards and manufacturer documentation (for example, Dycore [9] and Van Nieuwpoort [11]).
- Composite Slabs are governed by EN 1994 (Eurocode 4) [12], covering aspects such as bending, shear, deflection, shear connection, and fire resistance for composite steel–concrete structures.

Ensuring compliance with these Eurocodes is essential for meeting structural and serviceability requirements, including bending, shear capacity, deflection limits.

Accurately quantifying the most commonly used floor systems presents challenges due to the reluctance of the industry to disclose specific market share data. To address this limitation, scientific literature was used as an alternative means to determine which floor systems are widely used. By analyzing trends in research publications from 1990 to 2024, both globally and within the Netherlands, certain inferences can be made about the prevalence of specific floor systems in practice. This method assumes that research trends reflect industry practices to some extent.

Two graphs were created to illustrate these trends. Figure 2.1 shows global research interest in floor systems over the past three decades, while Figure 2.2 focuses on research conducted in the Netherlands [4]. These provide insights into floor systems most relevant to the Dutch market. By incorporating qualitative insights from industry professionals, this approach addresses the absence of concrete quantitative data.

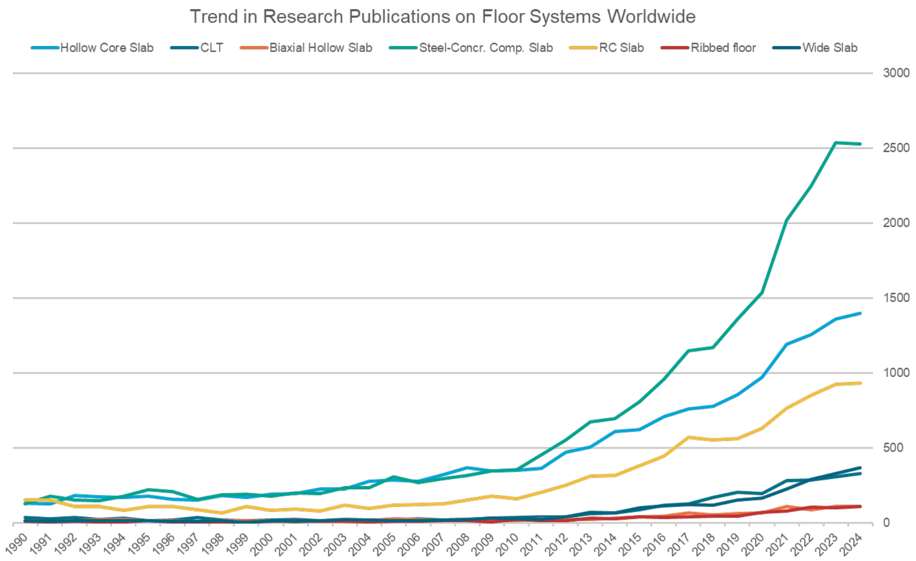


Figure 2.1: Trend in Research Publications on Floor Systems Worldwide [4]

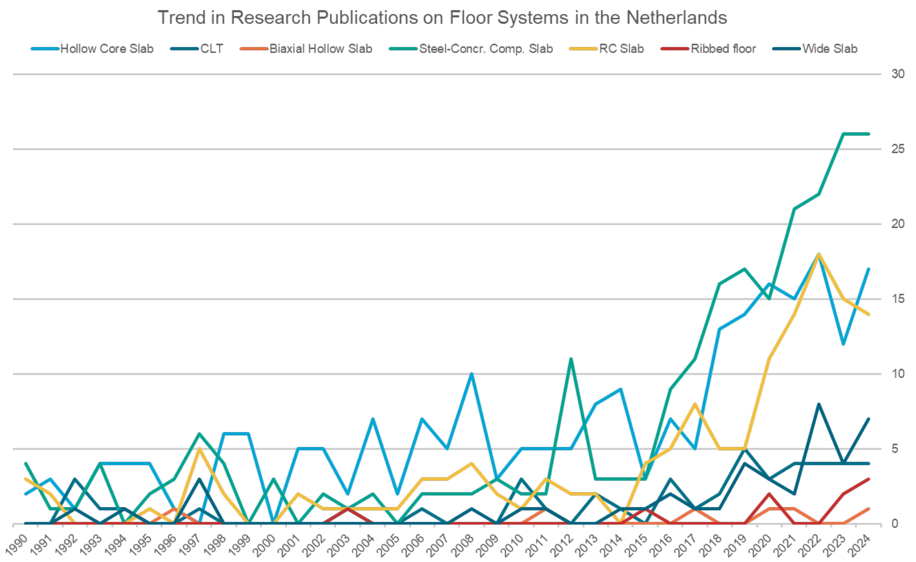


Figure 2.2: Trend in Research Publications on Floor Systems in the Netherlands [4]

The following subchapters delve into detailed descriptions of each concrete-based floor system, providing insights into their structural capabilities, sustainability attributes, and practical applications in various building types across the Netherlands.

2.1.1. Cast-in-Situ Concrete Floor

Solid, fully cast in-situ concrete floors provide unparalleled design flexibility, enabling designers to determine the layout of the floor plan and the position and shape of the supports. Point and linear supports can be combined in various patterns without requiring beams, as a cast in-situ floor can distribute loads in all directions. These floors are typically constructed with conventional reinforcement, using prefabricated nets alongside separate adjustment bars. The use of prestressed cast in-situ floors is uncommon due to higher costs and the system's vulnerability, such as difficulties with drilling openings.

The thickness of a cast in-situ floor can be adjusted according to the span and load combination. Generally, floor spans are limited to around 7 or 8 meters. For longer spans, the self-weight of the span becomes a significant factor, making other floor systems more viable. To prevent punching shear in heavily loaded columns from determining floor thickness, column heads or drop panels can be utilized. The monolithic nature of cast in-situ floors allows for effective distribution of local loads and ensures optimal horizontal stability.

By selecting the correct cover for the reinforcement, a fire resistance period of 120 minutes can be achieved. The construction of a fully cast in-situ floor requires formwork and propping, with the number of props determined by the floor's thickness and the formwork's strength and rigidity. Pipes and other installations can be integrated directly into the floor, and concrete core activation can also be incorporated into the design. The costs associated with cast in-situ concrete floors are primarily driven by labor expenses for creating and installing the formwork, while the amount of reinforcement required plays a secondary role [13].

Figure 2.3: Reinforced Cast In-Situ Concrete Slab [14]

2.1.2. Hollow Core Slab

Hollow core slabs offer numerous advantages across a variety of applications in residential, commercial, and industrial construction. The use of specific manufacturing equipment and rigorous quality control ensures that these slabs are of assured quality. One of the key benefits is their excellent lower surface finish, which is ready for painting due to the smooth steel formwork finish.

Installation of hollow core slabs is quick and easy. These slabs also offer excellent fire resistance, with the potential to achieve fire resistance ratings of up to 180 minutes by selecting appropriate thicknesses for the lower part of the element.

Hollow core slabs are designed for high load capacity and rigidity, experiencing minimal deformation even with high slenderness ratios due to their effective transverse load distribution. This is achieved despite using a low water/cement ratio in the concrete mix, which is essential for creating the desired cross sections without expensive formwork.

The reduced self-weight of hollow core slabs, thanks to their longitudinal voids, results in approximately 50% concrete savings compared to solid cast in-situ slabs, and a 30% reduction in the amount of prestressing steel required. This not only reduces material costs but also transportation costs due to lighter panels.

These slabs are easily adapted for mounting ancillary building systems such as electrical trays, water sprinklers, and HVAC systems. They also offer efficient span/depth ratios, leading to reduced storey heights, which maximizes the exploitation of available building space. For example, in a high-rise building, this efficiency can allow for an additional storey within the same overall building height.

Cost savings are another significant advantage, with large production volumes of uniform cross sections and rapid removal from casting beds after just 6-8 hours. This efficiency in production and material use leads to significant cost reductions.

Hollow core slabs provide high durability and load resistance due to advanced casting technologies and low water/cement ratios. They can span long distances without the need for temporary supports, allowing for immediate loading post-installation. Their excellent thermal properties and acoustic insulation make hollow core slabs ideal for reducing noise from external environments and providing sound separation between floors. Additionally, as a green product, they reduce the use of raw materials. High concrete and steel grades mean less material is needed to achieve the same load-bearing capacity as in-situ structures.

These slabs also offer flexibility in production, allowing for changes in dimensions and prestressed steel configurations according to technical specifications. This flexibility extends to seismic zones, where hollow core panels meet anti-seismic standards through steel reinforcement connections that create floor continuity without the need for concrete topping.

Overall, hollow core slabs are a versatile, cost-effective, and efficient choice for various construction needs, offering numerous benefits including high load capacity, fire resistance, and sustainability [15, 16].

Figure 2.4: Hollow Core Slab [17]

2.1.3. Biaxial Hollow Slab

Hollow biaxial slabs are reinforced concrete slabs with integrated voids to reduce concrete volume, addressing the high weight and limited span of traditional concrete slabs. These prefabricated slabs, containing hollow cylinders, are inexpensive and quick to install, suitable for residential, office, utility, and industrial buildings.

The carrying capacity of hollow biaxial slabs, such as those utilizing BubbleDeck technology, is significantly enhanced by reducing concrete usage by 35% while maintaining the same load-carrying capacity. Tests indicate that these slabs can achieve the same structural integrity with half the concrete required for a solid slab, or they can double the load capacity with only 65% of the concrete.

Shear resistance in hollow biaxial slabs is effectively maintained through the unique geometry of the ellipsoidal voids, which act like Roman arches. This design ensures that all the concrete remains effective, and any potential reduction in shear resistance is managed by excluding voids in high-shear areas, such as around columns and walls.

Fire resistance for these slabs can be tailored to last from 60 to 180 minutes, depending on the thickness of the concrete layer and the placement of rebar.

Overall, hollow biaxial slabs offer several advantages, including flexible design capabilities, the elimination of downstand beams and bearing walls, reduced construction costs, lower dead weight, and longer spans between columns. They also reduce construction dependency on weather conditions, require smaller foundations, and significantly cut concrete usage, promoting sustainability and efficiency in building projects [18, 19, 20].

Figure 2.5: Biaxial Hollow Slab [21]

2.1.4. Ribbed Floor

The ribbed floor is a pre-stressed, insulated system floor primarily used in residential and light commercial construction. This floor system is best suited for spans up to approximately 6 meters and is designed to handle average floor loads. The underside of the ribbed floor consists of a pre-formed EPS (expanded polystyrene) panel, which serves both as insulation material and as the mold for the cross-section of the concrete ribbed floor. The floor field is arranged based on standard panel widths of 1.2 and 0.9 meters, with additional in-situ concrete strips if necessary.

The ribbed floor system offers several advantages. It features a sustainable design with minimal material usage and a low self-weight. It is an attractive alternative to insulated hollow core slabs, particularly in residential construction [22, 23].

Figure 2.6: Ribbed Floor [24]

2.1.5. Wide Slab

The wide slab floor is a prefabricated concrete system reinforced with sheet reinforcement and lattice girders, commonly employed in residential and utility construction. During fabrication, a variety of openings and embedding provisions can be seamlessly integrated into the prefabricated shell of the wide slab. The thickness of a reinforced plank floor can be tailored according to the span and load requirements. Typically, similar to fully cast in-situ floors, this system is capable of spanning up to 8 meters.

On-site, a harness is attached to the lattice girders, facilitating the lifting and placement of the wide slab shell onto load-bearing walls or underlying structures supported by props. Beyond their role as lifting aids, the lattice girders impart significant strength and rigidity to the slab during the pouring of the concrete topping. They ensure strong cohesion between the prefabricated shell and the topping, while also supporting the installation of upper reinforcement bars [25].

Figure 2.7: Wide Slab [26]

2.1.6. Composite Slabs

Composite construction presents numerous advantages over traditional building methods. Firstly, it features a significantly faster and simpler construction process compared to conventional methods. Additionally, composite structures are lighter than traditional concrete buildings, leading to reduced material handling requirements on-site. Moreover, composite construction enables the creation of large column-free areas in buildings and longer spans, demonstrating its versatility and adaptability in various architectural contexts [27].

Composite slabs offer significant advantages in bending resistance and stiffness compared to conventional reinforced concrete slabs. This is due to the composite action, which optimally combines the strong material properties of different components, such as steel and concrete [28].

Shallow Deck Composite Slab

A shallow deck composite floor consists of thin, profiled steel sheeting onto which a reinforced concrete topping is cast in-situ. The steel sheeting serves as both formwork and reinforcement, with the 'dents' in the sheeting enabling composite action between the steel and concrete. The underside of the floor displays a ribbed structure, with rib spacing ranging from 200 to 300 mm. Due to its ribbed design, the floor bears loads in one direction and requires continuous linear support for bi-directional load-bearing. Overhangs can be created, and recesses are made either during construction by excluding concrete sections or after installation through drilling

Shallow deck composite floors typically span up to 6 meters, depending on the thickness of the steel sheeting and the concrete topping. The self-weight is about 80% of that of a solid concrete floor. Local load distribution is limited due to the ribbed structure and thin concrete layer, requiring additional support for concentrated loads. The reinforced concrete topping can act as a stability diaphragm, and fire resistance of up to 120 minutes can be achieved with additional reinforcement or by adjusting the floor thickness. Temporary propping is required for spans beyond 3 meters, and small installations, such as electrical conduits, can be integrated into the concrete topping [13, 29, 30].

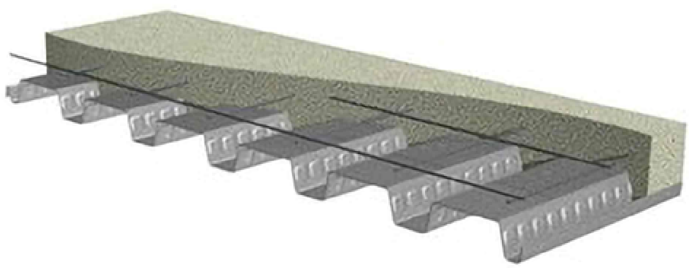


Figure 2.8: Shallow Deck Composite Slab [31]

Deep Deck Composite Slab

Deep deck composite floors operate on the same structural principle as shallow deck composite floors, with the key distinction being the significantly greater sheeting depth (approximately 200-225 mm) and a larger centre-to-centre rib spacing of about 600 mm. The total floor thickness, including the in-situ concrete topping, ranges from 280 mm to 350 mm.

These floors can span up to 8 meters, depending on the thickness of the steel sheeting and the concrete topping. The self-weight of the floor is approximately 50% of that of a solid concrete floor. Similar to shallow deck systems, the ribbed structure and thin concrete layer limit the distribution of local loads, so additional support may be required for concentrated loads.

The reinforced concrete topping can serve as a stability diaphragm, and fire resistance of up to 90 minutes can be achieved with additional reinforcement, especially in the ribs or at support points. Temporary propping is required for spans longer than 5 meters. Installations such as small pipes can be integrated into the cast concrete topping [13, 29].

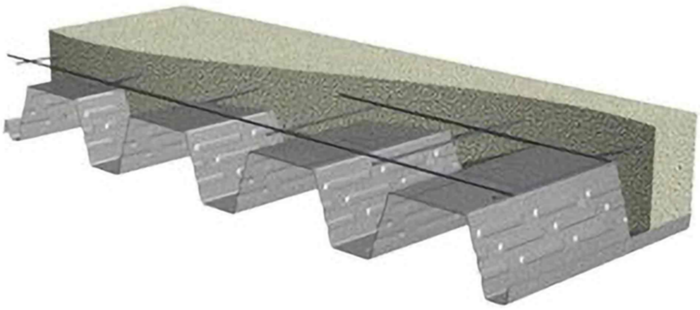


Figure 2.9: Deep Deck Composite Slab [31]

2.2. Concrete Strength Degradation

Understanding how concrete degrades over time is essential for evaluating the environmental impact of interventions required at the end of a building's life cycle. As concrete slabs experience strength reduction, determining the extent of degradation enables accurate calculation of the environmental footprint of necessary reinforcement or retrofitting. This prediction is vital for multi life-cycle assessments, where the total impact of maintaining and extending the structure's life must be accounted for.

The study conducted by Gao et al. [32] developed a probabilistic model to predict the long-term, time-dependent compressive strength of concrete in existing reinforced concrete buildings. The model addresses the degradation of concrete strength over time using field data from buildings of varying ages and environmental conditions. It combines destructive and non-destructive testing methods to establish a time-dependent function of compressive strength, providing insights into structural performance over time.

Data was collected from 33 buildings in Shanghai, China, comprising both residential and office buildings. These buildings were constructed between 1960 and 2010, offering a range of service ages from 1 to 60 years.

Two testing methods were employed: the rebound hammer method and core drilling. The rebound hammer method was applied to all 33 buildings, providing nondestructive estimates of surface compressive strength. Core drilling was performed on 27 of the 33 buildings to obtain direct measurements of compressive strength, which validated the rebound hammer results and helped refine the model. Testing focused on key structural elements, specifically beams, columns, and stairs, to assess strength degradation over time.

The buildings were located in Shanghai, characterized by a tropical monsoon climate with an average relative humidity of 75%. While these environmental conditions provided context for the degradation processes observed, the model focuses on time-dependent behavior of concrete under load, making it applicable for similar building types and loading conditions in other regions.

Gao's model [32] can be formulated as follows:

$$\mu_{R-1} = -2.0 \times 10^{-4} t^2 + 8.6 \times 10^{-3} t + 0.84$$
$$\mu_{C-1} = -3.0 \times 10^{-4} t^2 + 1.3 \times 10^{-2} t + 0.8819$$

where μ_R and μ_C are the dimensionless mean values of the strengths measured by the rebound and core drilling methods, respectively.

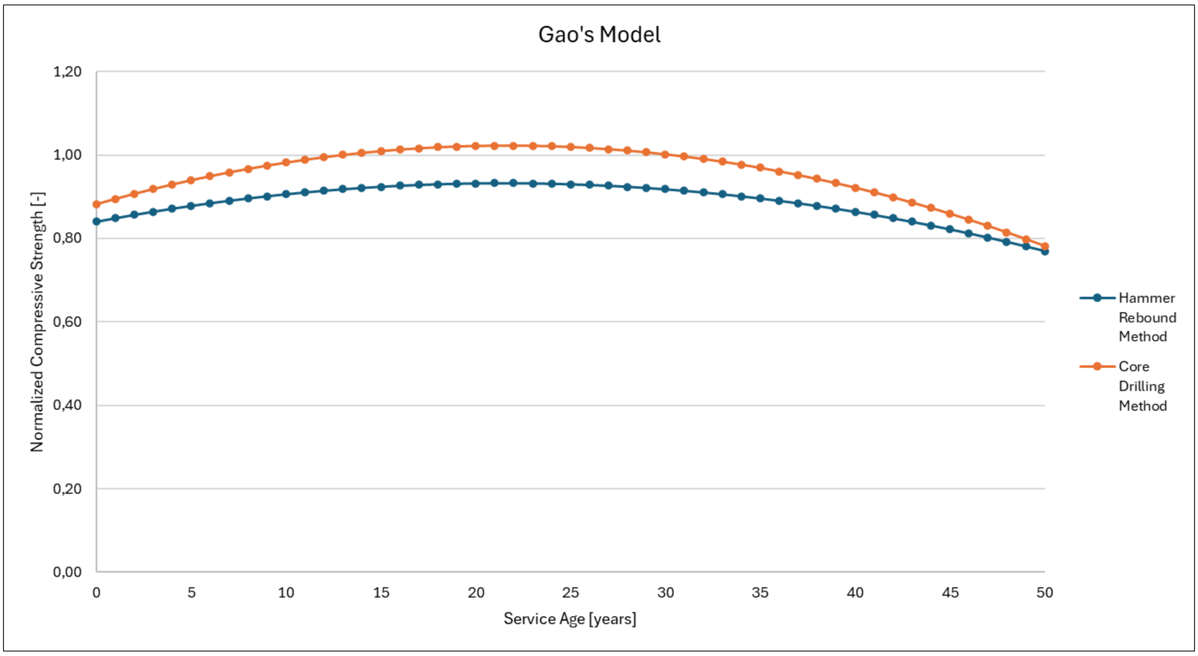


Figure 2.10: Gao's Model [32]

Gao's probabilistic model will be used in this research to predict compressive strength reduction for a multi life-cycle assessment. This model is suitable because it is based on real-world data from residential and office buildings with similar loading conditions. The model's combination of destructive and nondestructive testing provides a reliable framework for estimating strength reduction at the end of each life cycle.

The predicted strength reduction will inform the necessary intervention techniques for subsequent life cycles, such as reinforcement or retrofitting. This will enable the assessment of the environmental impact of these interventions, contributing to a more comprehensive evaluation of the total environmental impact across multiple life cycles of concrete floor systems.

2.3. Corrosion of Steel Reinforcement

Corrosion of steel reinforcement is a primary factor affecting the durability and longevity of reinforced concrete structures. In the alkaline environment of concrete, with a typical pH of around 12.5 to 13.5, steel reinforcement is protected by a thin passive oxide layer that inhibits corrosion. However, this protective environment can be compromised through a process known as carbonation [33].

Carbonation Process and pH Reduction

Carbonation occurs when carbon dioxide CO_2 from the atmosphere diffuses into the concrete and reacts with calcium hydroxide $(Ca(OH)_2)$, a product of cement hydration. The chemical reaction can be expressed as:

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O \tag{2.1}$$

This reaction leads to the formation of calcium carbonate $(CaCO_3)$ and water, resulting in a reduction of the concrete's pH. When the pH drops below approximately 9, the passive oxide layer on the steel reinforcement becomes unstable, rendering the steel susceptible to corrosion [33].

Corrosion Rate Parameters

To evaluate the effect of steel reinforcement corrosion on the structural performance over multiple life cycles, the following methodology was adopted:

Calculation of the Carbonation Depth

The carbonation depth D as a function of time t is calculated using the empirical relationship:

$$D = k\sqrt{t} \tag{2.2}$$

where:

- D = carbonation depth (mm)
- k = carbonation coefficient (-)
- t = time (years)

The rate at which carbonation progresses is characterized by the carbonation coefficient, denoted as k. In this study, a k value of 3.83 was identified from [34], based on carbonation depth measurements taken from 70 different concrete structures in Dhaka city. These measurements were obtained from various structural members, specifically slabs in the indoor environments of buildings.

For this study, the corrosion current density value was selected based on the environmental exposure conditions and data retrieved from [35]. The structure is located in an XC1 exposure class, representing an indoor environment with minimal risk of chloride-induced corrosion. For a crack width of 0.4 mm (the maximum allowable for the slabs according to Eurocode 2) and a chloride concentration of 0.6%, the tested value of 0.3836 $\mu\mathrm{A\,cm^{-2}}$ from [35] was adopted.

The time at which carbonation reaches the steel reinforcement (t_{cor}) is determined by setting $D = c$, where c is the concrete cover thickness:

$$t_{\text{cor}} = \left(\frac{c}{k}\right)^2 \tag{2.3}$$

Estimation of Corrosion Rate and Steel Loss

After carbonation reaches the reinforcement, corrosion begins at a rate defined by the corrosion current density (i_{corr}). The corrosion rate (V_{corr}) in mm/year is calculated using:

$$V_{\text{corr}} = 0.0116 \times i_{\text{corr}} \tag{2.4}$$

where:

- V_{corr} = corrosion rate (mm/year)
- i_{corr} = corrosion current density ($\mu\mathrm{A\,cm^{-2}}$)

Once carbonation reaches the steel reinforcement, the corrosion current density (i_{corr}) becomes a critical parameter. It quantifies the rate of corrosion in $\mu\mathrm{A\,cm^{-2}}$. Reported i_{corr} values for carbonation-induced corrosion range between 0.1 and $1\,\mu\mathrm{A\,cm^{-2}}$. A higher i_{corr} value indicates a more aggressive corrosion process.

The total corrosion penetration (p) over the period from corrosion initiation to the end of the service life (t) is:

$$p = V_{\text{corr}} \times (t - t_{\text{cor}}) \tag{2.5}$$

Reduction in Reinforcement Cross-Sectional Area

The loss in diameter of the steel reinforcement due to corrosion (Δd) is calculated as:

$$\Delta d = 2p \tag{2.6}$$

The remaining diameter ($d_{\text{remaining}}$) of the steel reinforcement is:

$$d_{\text{remaining}} = d_{\text{initial}} - \Delta d \tag{2.7}$$

where:

- d_{initial} = initial diameter of the reinforcement bar (mm)

The remaining cross-sectional area ($A_{\text{remaining}}$) is calculated using:

$$A_{\text{remaining}} = \frac{\pi}{4}\left(d_{\text{remaining}}\right)^2 \tag{2.8}$$

The percentage reduction in cross-sectional area is:

$$\text{Percentage Loss} = \left(\frac{A_{\text{initial}} - A_{\text{remaining}}}{A_{\text{initial}}}\right) \times 100\% \tag{2.9}$$

where:

- A_{initial} = initial cross-sectional area of the reinforcement bar (mm^2)

2.4. Intervention Techniques

Intervention techniques are essential for strengthening and rehabilitating existing slabs to ensure they meet structural demands when reused. These techniques apply to various slab types, including cast-in-situ concrete slabs, hollow core slabs, and composite slabs (steel profiled concrete slabs), allowing for continued safe use or adaptation to new load requirements.

2.4.1. Fiber-Reinforced Polymer (FRP) Strengthening

Fiber-Reinforced Polymer (FRP) Strengthening is a commonly used technique across all slab types. This method involves applying carbon or glass fiber materials to the slab's tension zone, typically the underside, to increase tensile and flexural strength without adding significant weight. It is effective for cast-in-situ concrete slabs, hollow core slabs, and composite slabs [36].

2.4.2. Post-Tensioning

Post-Tensioning, either external or internal, is another intervention technique suitable for cast-in-situ concrete slabs and hollow core slabs. It involves installing tensioned steel cables or tendons to introduce compressive forces into the slab, thereby improving its load-bearing and flexural capacities. This technique is particularly useful when addressing deflection issues or increasing overall strength [37].

2.4.3. Concrete Jacketing

For cast-in-situ concrete slabs and composite slabs, Concrete Jacketing or Overlay can be employed. This involves applying an additional reinforced concrete layer to the top or bottom of the slab, thickening it and enhancing its load-bearing capabilities. While effective, this approach increases the weight of the slab, which must be carefully considered during design [38].

2.4.4. Grouting of Hollow Cores

Hollow core slabs benefit from specialized techniques such as Grouting or Foam Filling of Hollow Cores, where grout or lightweight foam is injected into the slab's internal voids. This increases stiffness, reduces deflection, and allows the slab to support higher loads. Additionally, Shear Key Enhancement, which strengthens the shear keys between adjacent hollow core slabs, is useful for improving load distribution across the slabs [39].

2.4.5. Epoxy Injection

For cracked cast-in-situ slabs, Epoxy Injection for Crack Repair is a common intervention. High-strength epoxy resin is injected into cracks to restore structural integrity by bonding and sealing the cracks, thus preventing further deterioration [40].

2.4.6. Steel Plate Bonding

Steel Plate Bonding is a technique primarily used to increase the flexural strength of cast-in-situ, and hollow core slabs. This method involves bonding steel plates to the tensioned side of the slab, usually the underside, enhancing load performance. It is particularly effective when combined with other strengthening techniques [41].

Steel plate bonding significantly improves both flexural and shear capacities by connecting steel plates to stressed areas of concrete structures using high-strength epoxy adhesives. This method not only utilizes the steel's full strength but also mitigates existing cracks and controls deformation, increasing both crack resistance and structural stiffness. The plates are typically positioned at the tension side of beams and slabs, where they are most effective in resisting tensile stresses [42, 43, 44].

Design considerations include ensuring sufficient bond strength to withstand anticipated loads and preventing shear failure in the concrete. Methods such as using clamping bolts or anchoring plates at the ends of the steel plates help secure the bond and prevent debonding [42].

The plates are generally thin and wide, about 4mm to 6mm thick, to adhere closely to the component's surface, while thicker plates may be used to enhance shear capacity depending on specific structural requirements [42, 43].

Empirical studies, including those on perforated steel plates as alternatives to traditional reinforcement, have demonstrated significant increases in load capacity (by 43% to 76%) and reductions in crack widths, underscoring the effectiveness of this technique [45].

Steel plate bonding stands out as a robust method for extending the service life and functional capacity of concrete structures, making it a preferred choice for retrofitting and strengthening projects.

2.5. Allocation Methods

In life cycle assessments (LCA) for buildings, allocation methods play a crucial role in determining how environmental impacts are distributed across the various stages of a building component's life. This is especially important in situations where building materials are reused or recycled across multiple life cycles. Several allocation methods have been developed, each with different approaches to how impacts are assigned to the initial, intermediate, and final uses of building components. The key allocation methods relevant to this study include the following [46]:

The cut-off method allocates 100% of the environmental impacts from the production of materials to the first life cycle of the component, with no impacts attributed to subsequent reuse. This method is commonly used when the focus is on rewarding the initial project for material use while highlighting the environmental benefits of reusing components in later projects without adding additional burdens. It effectively encourages upstream reuse and ensures that the environmental savings from preventing new material production are credited to the first user of the materials.

In contrast, the end-of-life method shifts the environmental impact burden to the final life cycle of the building component. Here, the initial life cycle bears none of the production-related impacts, which are instead attributed entirely to the component's end of life. This method encourages designing for downstream reuse, as the final project bears the environmental burden of using and disposing of the material, rather than the initial one.

The distributed allocation method, based on the PAS-2050 standard, allocates the production and end-of-life impacts across all life cycles, distributing them equally. This approach takes into account the fact that materials can have multiple reuse cycles and ensures that each life cycle bears a portion of the environmental impacts. However, this method relies on accurate predictions of how many life cycles a material will go through, which can introduce uncertainty into the assessment.

The EC EF method builds on the European Commission's Product Environmental Footprint initiative. It allocates production and end-of-life impacts equally between the first and last life cycles, sharing the environmental burdens more evenly across the material's lifespan. This method addresses some of the limitations of both the cut-off and end-of-life methods by providing a balanced view of the impacts over time.

The degressive method is a hybrid approach, combining elements of both the distributed allocation and EC EF methods. It applies a gradual reduction of the environmental impacts allocated to each life cycle, depending on the predicted number of cycles. This method allows for a more dynamic distribution of impacts, reducing the burden on later life cycles as materials are reused multiple times.

The SIA 2032 method, used in Switzerland, allocates impacts based on the actual lifespan of the component in each building use. For example, if a building component is used for 20 years in one project and 10 years in the next, the impacts are distributed proportionally based on these time frames. This method provides a more lifespan-specific approach, requiring detailed data on the expected life cycles of building components.

Each of these allocation methods provides a different approach to distributing environmental impacts across the life cycles of building materials. The choice of method significantly influences the outcome of an LCA, particularly in projects where reuse plays a key role. In the context of this study, careful consideration of these methods is crucial to ensuring that the environmental benefits of reuse are accurately captured and that the allocation method aligns with the research objectives. Figure 2.11 gives an overview of the different allocation methods and their allocation of the life cycle stages to the relevant cycle [46].

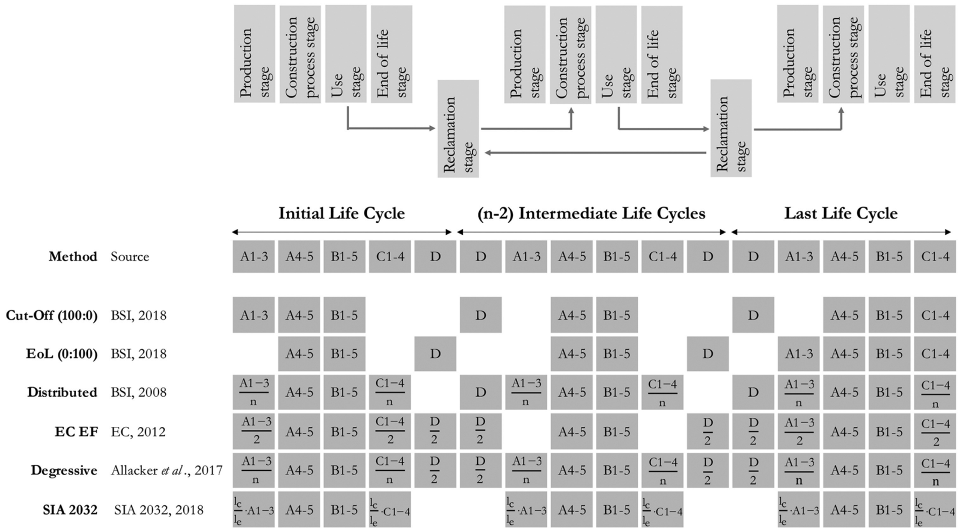


Figure 2.11: Overview of Allocation Methods [46]

2.6. Environmental Impact Categories

Environmental impact categories are essential in lifecycle assessments (LCA) as they group specific environmental issues into measurable indicators. These categories allow for the systematic evaluation of environmental burdens associated with materials and products, providing insights into their ecological impact. The EN 15804 standard [47], a widely used framework for Environmental Product Declarations (EPDs), organizes these categories to assess the environmental performance of building materials. Initially, the standard utilized a set of 11 impact categories (Set A1), but in 2019, it was revised to include 19 categories (Set A2) to reflect advances in scientific methodology.

2.6.1. Set A1

The original EN 15804+A1 [48] set comprises 11 categories that assess diverse environmental impacts. The first is Global Warming Potential (GWP), which measures the contribution of greenhouse gas emissions to climate change. This indicator quantifies the potential global warming effect in kilograms of CO_2 equivalents, highlighting the role of materials and processes in exacerbating or mitigating climate change.

Ozone Depletion Potential (ODP) focuses on the emissions that damage the stratospheric ozone layer, which protects life on Earth from harmful ultraviolet radiation. This category is expressed in kilograms of CFC-11 equivalents, capturing the impact of substances such as chlorofluorocarbons.

Acidification Potential (AP) evaluates the potential acidification of soil and water ecosystems caused by emissions of nitrogen oxides (NO_2) and sulfur oxides (SO_2). These emissions, commonly from industrial and transportation sources, are expressed in kilograms of SO_2 equivalents and are known to harm vegetation, aquatic life, and infrastructure.

Eutrophication Potential (EP) measures the enrichment of ecosystems with nutrients like nitrogen and phosphorus, which can disrupt the balance of freshwater and marine ecosystems. This category is expressed in kilograms of phosphate (PO_4^{3-}) equivalents and highlights the consequences of nutrient runoff from agricultural or industrial activities.

Photochemical Ozone Creation Potential (POCP), also known as summer smog, addresses the formation of ground-level ozone through reactions between volatile organic compounds (VOCs) and sunlight. This is expressed in kilograms of ethene (C_2H_4) equivalents, reflecting its effects on human health and vegetation.

Abiotic Depletion Potential for Fossil Fuels (ADP-fossil) assesses the depletion of non-renewable fossil fuel resources, expressed in kilograms of antimony (Sb) equivalents.

Abiotic Depletion Potential for Minerals and Metals (ADP-minerals) measures the depletion of natural resources such as antimony and other critical minerals. The results are expressed in kilograms of antimony (Sb) equivalents, underlining the sustainability challenges of resource-intensive industries.

Human Toxicity Potential (HTP) evaluates the potential health risks posed by toxic substances released into the environment. This category is expressed in kilograms of 1,4-dichlorobenzene equivalents, covering pollutants that can lead to chronic health effects.

Freshwater Aquatic Ecotoxicity Potential (FAETP) assesses the harmful effects of pollutants on freshwater organisms, expressed in kilograms of 1,4-dichlorobenzene equivalents. This category captures the ecological consequences of toxic discharges into rivers and lakes.

Marine Aquatic Ecotoxicity Potential (MAETP) evaluates the impact of toxic substances on marine ecosystems. Like FAETP, it is expressed in kilograms of 1,4-dichlorobenzene equivalents and focuses on pollutants that harm oceanic species.

Terrestrial Ecotoxicity Potential (TETP) measures the impact of pollutants on land ecosystems, capturing the potential harm to soil-dwelling organisms. This category is also expressed in kilograms of 1,4-dichlorobenzene equivalents and emphasizes the effects of pesticides and heavy metals [49]. An overview of the set a1 categories with the unis is given in Table 2.1.

Table 2.1: Impact Categories for Set A1

SET A1	Description	Unit
ADP-minerals&metals	Depletion of abiotic resources minerals and metals	Kg Sb Eq
ADP-fossil	Depletion of abiotic resources fossil fuels	Kg Sb Eq
GWP	Climate change	Kg CO2 Eq
ODP	Ozone layer depletion	Kg CFC-11 Eq
POCP	Photochemical Oxidation	Kg C2H4 Eq
AP	Acidification	Kg SO2 Eq
EP	Eutrophication	Kg PO4 Eq
HTP	Human Toxicity	Kg 1,4-DCB Eq
FAETP	Freshwater Aquatic Ecotoxicity	Kg 1,4-DCB Eq
MAETP	Marine Aquatic Ecotoxicity	Kg 1,4-DCB Eq
TETP	Terrestrial Ecotoxicity	Kg 1,4-DCB Eq
ECI	Environmental Cost Indicator	€

2.6.2. Set A2

The transition to the EN 15804+A2 [50] set of environmental impact categories, which is expected to become mandatory on July 1, 2025, introduces several important updates. These changes include not only modifications to the categories themselves and their subdivisions but also adjustments to the units of measurement and calculation methods. The new system is based on modern scientific methods and aligns with the Product Environmental Footprint (PEF), a framework adopted by the European Commission to evaluate the environmental performance of products, including construction materials [51].

One major update is the refinement of key categories such as acidification, eutrophication, summer smog, human toxicity, and ecotoxicity. These categories have been divided into sub-indicators, offering a more detailed analysis of specific impacts. For example, eutrophication is now assessed separately for terrestrial, marine, and freshwater ecosystems to better represent the unique effects on each environment. Similarly, human toxicity and ecotoxicity are divided into carcinogenic and non-carcinogenic impacts, as well as specific toxicity indicators for different ecosystems [52].

Changes in units of measurement have also been made to ensure greater accuracy and consistency. Acidification, previously measured in kilograms of SO_2 equivalents, is now expressed in moles of H+ equivalents. Eutrophication has separate units for its subcategories, such as kilograms of phosphorus (P) for freshwater and kilograms of nitrogen (N) for marine impacts. These adjustments improve the precision of environmental assessments.

The methods for calculating some categories have also evolved. Global Warming Potential (GWP), which was previously a single indicator, is now divided into three subcategories: fossil-based, biogenic, and emissions from land use changes. This provides a clearer understanding of the sources of greenhouse gas emissions. Similarly, the category for photochemical ozone formation, previously referred to as summer smog, has been updated with more accurate calculations tailored to specific regions.

These changes have significant implications for the environmental profiles of construction products and materials. Since the environmental performance of a material is derived from its environmental profile, updates to the categories and methodologies result in changes to how the material's overall impact is calculated [52, 53, 54]. An overview of the set a2 categories with the unis is given in Table 2.2.

Table 2.2: Impact Categories for Set A2

SET A2	Description	Unit
GWP-total	Global Warming Potential total	Kg CO2 Eq
GWP-fossil	Global Warming Potential fossil fuels	Kg CO2 Eq
GWP-biogenic	Global Warming Potential biogenic	Kg CO2 Eq
GWP-luluc	Global Warming Potential land use	Kg CO2 Eq
ODP	Depletion potential of the stratospheric ozone layer	Kg CFC 11 Eq
AP	Acidification potential	Mol H+ Eq
EP-freshwater	Eutrophication potential, freshwater	Kg PO4 Eq
EP-marine	Eutrophication potential, marine	Kg N Eq
EP-terrestrial	Eutrophication potential, terrestrial	Mol N Eq
POCP	Formation potential of tropospheric ozone	Kg NMVOC Eq
ADP-minerals&metals	Abiotic depletion potential for non-fossil resources	Kg Sb Eq
ADP-fossil	Abiotic depletion for fossil resources potential	MJ, net calorific value
WDP	Water (user) deprivation potential	m^3 world Eq deprived
PM	Potential incidence of disease due to PM emissions	Disease incidence
IRP	Potential Human exposure efficiency relative to U235	kBq U235 Eq
ETP-fw	Potential Comparative Toxic Unit for ecosystems	CTUe
HTP-c	Potential Comparative Toxic Unit for humans cancerous	CTUh
HTP-nc	Potential Comparative Toxic Unit for humans non-canc.	CTUh
SQP	Potential soil quality index	Dimensionless
ECI	Environmental Cost Indicator	€

2.7. Shadow Pricing Method

The shadow pricing method provides a monetary representation of the environmental impacts associated with materials, products, or projects. By assigning financial values to these impacts, shadow pricing enables better comparison and communication of sustainability performance.

In Life Cycle Assessments (LCA), shadow pricing is used to consolidate environmental impacts into a single monetary value. The impacts are categorized under defined environmental categories, each of which is assigned a shadow price or Environmental Cost Indicator (ECI). Table 2.3 presents the ECI values for the environmental impact categories of set A1. These values are calculated by weighting the severity of each impact and expressing them in a standardized monetary unit, such as euros. The total shadow cost is then determined by aggregating the individual costs for all categories, enabling a simplified yet comprehensive assessment of a material's environmental footprint.

Environmental Impact Category	Unit	Weighting Factor (€ / unit indicator)
Global Warming Potential	kg CO_2-eq	0.05
Ozone Layer Depletion Potential	kg CFC11-eq	30.00
Acidification Potential	kg SO_2-eq	4.00
Eutrophication Potential	kg PO_4^{3-}-eq	9.00
Abiotic Depletion Potential Minerals and Metals	kg SB-eq	0.15
Abiotic Depletion Potential Fossil Fuels	kg SB-eq	0.15
Human Toxicity Potential	kg 1,4 DB-eq	0.09
Freshwater Aquatic Ecotoxicity Potential	kg 1,4 DB-eq	0.03
Marine Aquatic Ecotoxicity Potential	kg 1,4 DB-eq	0.0001
Terrestrial Ecotoxicity Potential	1.4 DB-eq	0.06
Photochemical Oxidation Potential	kg C_2H_4	2.00

Table 2.3: ECI Values for Set A1 Environmental Impact Categories [55]

In the Dutch construction industry, shadow pricing is crucial for regulatory metrics like the Environmental Performance of Buildings (MPG) and the Environmental Cost Indicator (MKI). The MPG measures the shadow costs for all materials used in a building, normalized by floor area in euros per square meter per year, while the MKI assesses individual products or projects. These metrics play a significant role in evaluating sustainability during construction projects and procurement processes.

With the introduction of the expanded A2 environmental impact categories, a new weighting set for environmental costs has been developed by CE Delft. This updated set reflects the additional categories and refined metrics introduced in EN 15804+A2. Table 2.4 presents the new weighing factors for the ECI, offering a more detailed and accurate assessment framework for lifecycle environmental costs. These updates ensure the continued relevance and precision of shadow pricing in aligning with modern sustainability goals.

Environmental Impact Category	Unit	Weighting Factor (€ / unit indicator)
Global Warming Potential Total	kg CO_2-eq	0.116
Global Warming Potential Fossil Fuels	kg CO_2-eq	0.116
Global Warming Potential Biogenic	kg CO_2-eq	0.116
Global Warming Potential Land Use	kg CO_2-eq	0.116
Ozone Layer Depletion Potential	kg CFC11-eq	32.00
Acidification Potential	mol H^+-eq	0.39
Eutrophication Potential Freshwater	kg P-eq	1.96
Eutrophication Potential Marine	kg N-eq	3.28
Eutrophication Potential Terrestrial	mol N-eq	0.36
Photochemical Oxidation Potential	kg NMVOC-eq	1.22
Abiotic Depletion Potential Minerals and Metals	kg Sb-eq	0.30
Abiotic Depletion Potential Fossil Fuels	MJ, net cal. val.	0.00033
Water (user) Deprivation Potential	m^3 world eq deprived	0.00506
Potential Incidence of Disease due to PM Emissions	Disease incidence	575838
Potential Human Exposure Efficiency Relative to U235	kBq U235-eq	0.049
Freshwater Aquatic Ecotoxicity Potential	CTUe	0.00013
Human Toxicity Potential Carcinogenic	CTUh	1090638
Human Toxicity Potential Non-Carcinogenic	CTUh	147588
Potential Soil Quality Index	Dimensionless	0.000178

Table 2.4: ECI Values for Set A2 Environmental Impact Categories [55]

2.8. Similar Studies

Significant literature exists that evaluates existing slab floor configurations or suggests innovative alternatives.

One of the studies [56] compares environmental impacts of building floor rehabilitation systems (timber floors, RC slab, beam-and-block slab, steel-concrete composite slab and a GFRP sandwich panel) using LCA. Timber is found to be the most environmentally friendly option, while steel–concrete composite floors and RC are behind in various categories. The GFRP system performs poorly overall.

[57] compares the environmental and economic impacts of four different slab types: lightweight steel composite decking, hollow core precast floor, the Cofradal 200 floor slab, and the proposed hybrid GLT-Concrete floor. The evaluation results reveal that the GLT-Concrete slab exhibits lower emissions across all assessed environmental categories. Additionally, the life cycle cost analysis (LCC) indicates that despite its higher initial construction cost, choosing the proposed GLT-Concrete slab, with end-of-life reuse considerations, results in a lower overall cost.

According to [58], in the context of residential buildings, the environmental impact of structures featuring precast hollow core concrete floors is asserted to be 12.2% lower compared to those with cast-in-situ floors, based on the defined functional unit using the LCA methodology.

Another research [59] compares three flooring systems: Cofradal260 prefabricated, hollow core precast, and a proposed prefabricated ultra-shallow flooring system (PUSS). Results indicate that the proposed system exhibits lower embodied energy and GHG emissions compared to both Cofradal260 and hollow core precast. Additionally, life cycle analysis demonstrates reductions in construction costs and end-of-life costs in comparison to both Cofradal260 and hollow core precast.

The comparative study [60] between prefabricated concrete composite slabs and cast-in-place floor slabs in two residential buildings revealed that the former had lower carbon emissions during both production and construction stages, with a notable difference observed between the two.

[61] conducted LCA studies on three different slabs for high-rise buildings, namely: slat slab roof, hollow core slab floor, and a steel composite floor slab. They showed that the hollow core slab floor had the overall lowest environmental impact and calculated the shadow pricing cost of the whole building.

2.9. Research Gap

Despite the significant role that floor systems play in the overall environmental impact of buildings, there is a notable scarcity of research focused specifically on the environmental impact assessment of these systems, particularly within the context of the Netherlands. Existing studies often do not consider multiple life cycles, thereby neglecting the potential environmental benefits or challenges associated with the reuse of floor systems over time. This gap is critical, as it overlooks the long-term sustainability implications of floor systems designed for reuse, especially within circular economy models.

In addition, potential degradation factors due to the reuse of floor systems, such as reduction in concrete strength and corrosion of steel reinforcement, are rarely explored in the current literature. These factors are crucial for understanding the structural integrity and longevity of reused floor systems, and their omission represents a significant gap in existing research.

Additionally, with the forthcoming implementation of the more comprehensive Set A2 environmental impact categories in the Netherlands, scheduled for 1 July 2025, there is a need for studies that assess floor systems using these updated categories. The Set A2 categories offer a more detailed and holistic evaluation of environmental impacts, but limited research has incorporated them, hindering our understanding of how different floor systems will perform under the new assessment framework.

Consequently, this study aims to address these gaps by conducting a comprehensive environmental impact assessment of various concrete-based floor systems within the Dutch context. The research will:

- **Consider Multiple Life Cycles**: By analyzing floor systems over three life cycles of each 50 years, the study will provide insights into the long-term sustainability and environmental performance of systems that can be reused, aligning with circular economy principles.

- **Assess Degradation Factors Due to Reuse**: The research will investigate potential degradation factors such as concrete strength reduction and steel reinforcement corrosion, evaluating how these affect the structural performance and environmental impact over time.
- **Incorporate Both Set A1 and Set A2 Environmental Impact Categories**: By evaluating floor systems using both the current Set A1 categories and the upcoming Set A2 categories, the study will offer a comprehensive assessment that is relevant for both present and future regulatory frameworks.

By integrating these elements, this research will fill existing gaps in the literature, providing a nuanced understanding of the environmental impacts and structural considerations of concrete-based floor systems over multiple life cycles. This will contribute valuable knowledge to the field, supporting the development of more sustainable construction practices in the Netherlands and beyond.

2.10. Summary

This literature review revealed a significant lack of studies focusing on the environmental impact assessment of floor systems in the Netherlands, particularly regarding multiple life cycles and the effects of degradation due to reuse. The common floor systems were analyzed, along with the mechanisms of concrete strength reduction and steel reinforcement corrosion that affect their longevity. Intervention techniques to enhance the reuse potential of these systems were discussed, emphasizing the importance of structural considerations in sustainability assessments. The chapter also examined allocation methods in life cycle assessments and the environmental impact categories defined by EN 15804, including the upcoming Set A2 categories. Identifying these research gaps highlights the need for comprehensive studies that integrate environmental and structural factors over multiple life cycles, which this study aims to fulfill.

3

Design of the Floor Systems

This chapter presents the design and analysis of three different floor systems using a standardized case study of a simply supported slab under typical office loading conditions. By applying consistent design parameters and methodologies in accordance with Eurocode standards, the chapter provides a comparative evaluation of the structural performance and material requirements of each floor system. The results of the analysis are presented at the end of the chapter and offering insights into the structural efficiency and suitability for reuse of each floor system.

3.1. Methodology for Comparison

This study compares three floor systems (cast-in-situ concrete slab, hollow core slab, and deep deck composite slab) under standardized office loading conditions. These systems were selected for their widespread use and represent diverse construction methods commonly employed in the Netherlands.

Table 3.1: Design and Loading Parameters for Comparison

Parameter	**Value or Criterion**
Span Length	5.4 m
Width	2.5 m
Consequence Class	CC2 ([62])
Variable Load	2.5 kN/m^2 ([62])
Unity Check (Bending Moment)	0.8

All floor systems were designed according to Eurocode standards to ensure consistency in loading conditions and structural dimensions. The structural system for each floor type was a simply supported slab, reflecting typical office building layouts. Uniform loads were applied, with the permanent load consisting solely of the self-weight of the slab and the variable load defined as per Eurocode requirements for office buildings.

The design of the slabs primarily focused on achieving a bending moment unity check of 0.8 to ensure efficient capacity utilization while maintaining a consistent safety margin:

$$\text{Unity Check} = \frac{M_{\text{Ed}}}{M_{\text{Rd}}} = 0.8 \tag{3.1}$$

While bending moment was the primary criterion for comparability, shear force and deflection were also checked to ensure compliance with Eurocode provisions. This step confirmed that all slabs met the required serviceability and safety standards.

The design of each slab type focused on optimizing material efficiency while meeting structural requirements. This methodology ensures that observed differences in performance or environmental impact arise solely from the intrinsic properties of the floor systems and not from inconsistencies in the design approach or loading conditions. The standardized parameters provide a robust and fair basis for comparing the structural efficiency and sustainability of each system.

3.2. Cast In-Situ Concrete Slab

The cast-in-situ concrete slab is designed to meet the requirements of bending resistance and serviceability under the specified loading conditions, adhering to Eurocode 2 (EN 1992-1-1:2004) [5] for the design of concrete structures. This slab is permanently connected to the steel beam using welded shear connectors, and reusing reinforced cast-in-situ concrete slabs in new structures remains rare today [63], aligning with the principles of a linear building economy. As such, it is not intended for reuse across multiple life cycles. The design process involves calculating the reinforcement required to resist the bending moments induced by both dead and live loads, utilizing the load combinations and partial safety factors specified in the Eurocode. The reinforcement layout and design checks are summarized in Table 3.2.

Table 3.2: Eurocode Design Checks for Cast In-Situ Concrete Slab

Eurocode Clause	Description
EC0 NA A1 [64]	Application to buildings.
EC2 3.1 [5]	Guidelines on concrete properties and classes.
EC2 3.2 [5]	Specifications for reinforcement steel properties.
EC2 4.4 [5]	Methods for verifying design calculations.
EC2 6.1 [5]	Design procedures for bending moments.
EC2 6.2 [5]	Design guidelines for shear resistance.
EC2 7.4 [5]	Limits and requirements for slab deflections.

The slab's concrete strength and reinforcement layout are detailed in Table 3.3.

Table 3.3: Composition of Cast In-Situ Concrete Slab

Component	Specification	Details
Concrete Strength	C20/25	Concrete cast in situ
Bottom Reinforcement	Ø10 mm bars	Spaced at 100 mm centers (Ø10-100)
Top Reinforcement	Ø8 mm bars	Spaced at 150 mm centers (Ø8-150)

Detailed calculations for this design, including bending moments, reinforcement calculations, and deflection checks, are available in Appendix A. The corresponding Excel calculations for this slab are provided in Appendix E. Figures 3.1 and 3.2 present the side view and front view of the cast-in-situ concrete slab, respectively, illustrating the reinforcement layout and the dimensions of the slab.

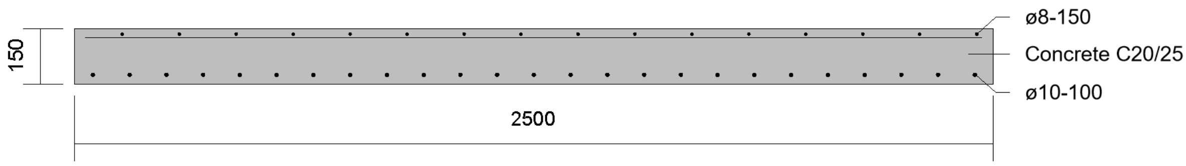


Figure 3.1: Cast In-Situ Slab Side View

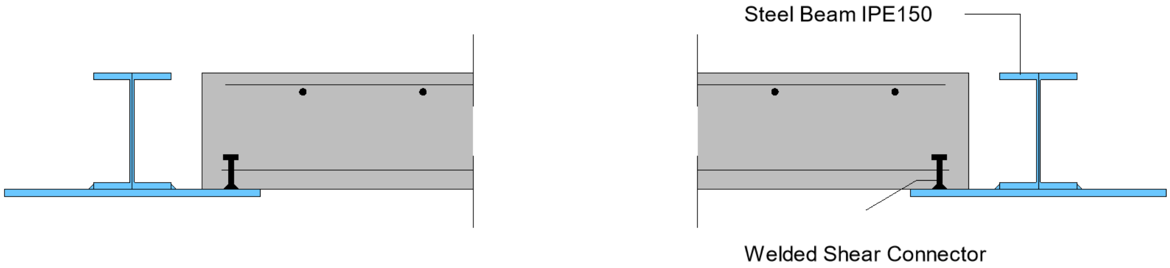


Figure 3.2: Cast In-Situ Slab Front View

3.3. Prefabricated Hollow Core Concrete Slab

The hollow core slab is a precast concrete element designed to be lightweight yet structurally efficient. The design relies on prestressed tendons (FeB1770) at the bottom of the slab, with additional reinforcement at the top to control cracking. This slab is connected to the steel beam using demountable shear connectors, facilitating disassembly and reuse. This feature aligns with the principles of a circular building economy, supporting the slab's adaptability for multiple life cycles. The slab is designed for the specified loads by ensuring sufficient bending resistance and minimal deflection, adhering to Eurocode 2 (EN 1992-1-1:2004) [5] for the design of concrete structures. The design process involves calculating the reinforcement required to resist the bending moments induced by both dead and live loads, utilizing the load combinations and partial safety factors specified in the Eurocode. The reinforcement layout and design checks are summarized in Table 3.4.

Table 3.4: Eurocode Design Checks for Prefabricated Hollow Core Concrete Slab

Eurocode Clause	Description
EC0 NA A1 [64]	Application to buildings
EC2 3.1 [5]	Guidelines on concrete properties and classes
EC2 3.2 [5]	Specifications for reinforcement steel properties
EC2 3.3 [5]	Specifications for prestressing steel properties
EC2 4.4 [5]	Methods for verifying design calculations
EC2 6.1 [5]	Design procedures for bending moments
EC2 6.2 [5]	Design guidelines for shear resistance
EC2 7.4 [5]	Limits and requirements for slab deflections

The slab's concrete strength, prestressed tendons, and reinforcement layout are detailed in Table 3.5.

Table 3.5: Composition of Prefabricated Hollow Core Concrete Slab

Component	Specification	Details
Concrete Strength	C20/25	Concrete cast in precast hollow core
Bottom Prestressing Tendons	FeB1770 Ø5 mm strands	Spaced at 100 mm centers (Ø5-100)
Top Prestressing Tendons	FeB1770 Ø5 mm strands	Spaced at 500 mm centers (Ø5-500)
Bottom Reinforcement	Ø10 mm bars	Spaced at 300 mm centers (Ø10-300)
Top Reinforcement	Ø8 mm bars	Spaced at 150 mm centers (Ø8-150)

Detailed design calculations for the hollow core slab, including bending moment analysis, reinforcement detailing, and shear capacity checks, are available in Appendix B. The corresponding Excel calculations for this slab are provided in Appendix E. Figures 3.3 and 3.4 show the side view and front view of the hollow core slab, highlighting the voids and reinforcement details.

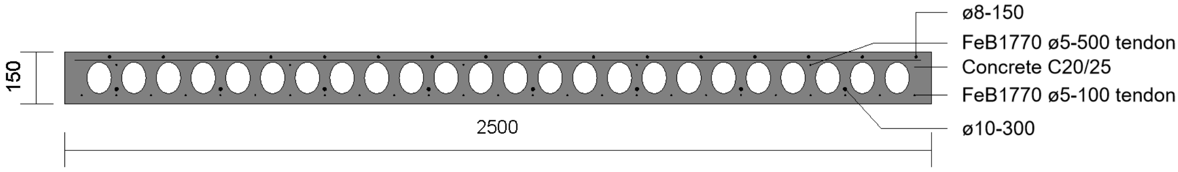


Figure 3.3: Prefabricated Hollow Core Slab Side View

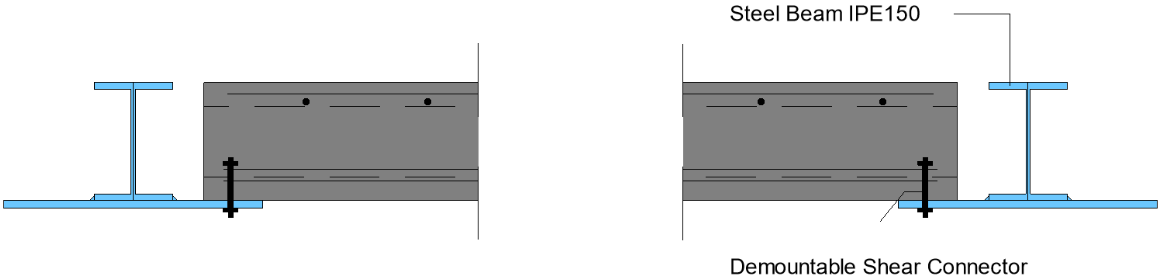


Figure 3.4: Prefabricated Hollow Core Slab Front View

3.4. Deep Deck Composite Slab

The deep deck composite slab is designed by combining steel decking with a concrete topping to create composite action that improves the structural efficiency of the floor system. The steel sheeting provides tensile resistance during construction and, once the concrete hardens, contributes to the bending resistance through composite action with the concrete topping. This slab is connected to the steel beam using demountable shear connectors, ensuring ease of disassembly and reuse. This connection method aligns with circular economy principles, facilitating its adaptation for multiple life cycles. The slab is designed for the specified loads by ensuring sufficient bending resistance and minimal deflection, adhering to Eurocode 4 (EN 1994-1-1:2005) [12] for the design of composite steel and concrete structures. The design checks are summarized in Table 3.6. The slab's layout is detailed in Table 3.7.

Table 3.6: Eurocode Design Checks for Deep Deck Composite Slab

Eurocode Clause	Description
EC0 NA A1 [64]	Application to buildings
EC4 3.2 [12]	Specifications for reinforcing steel
EC4 9.4 [12]	Analysis of internal forces and moments
EC4 9.5 [12]	Verification of steel sheeting for Ultimate Limit States
EC4 9.6 [12]	Verification of steel sheeting for Serviceability Limit States
EC4 9.7 [12]	Verification of composite slabs for ULS
EC4 9.7.1 [12]	Design criterion for composite slabs
EC4 9.7.2 [12]	Flexural design guidelines
EC4 9.7.5 [12]	Requirements for vertical shear capacity
EC4 9.8 [12]	Verification of composite slabs for SLS
EC4 9.8.1 [12]	Control of concrete cracking
EC4 9.8.2 [12]	Deflection control measures

Table 3.7: Composition of Deep Deck Composite Slab

Component	Specification	Details
Concrete Strength	C20/25	Concrete cast in situ
Steel Sheeting	S275, 1 mm thick	Galvanized, profiled steel sheeting
Bottom Tensile Reinforcement	Ø6 mm bars	Placed within the ribs of the steel decking
Top Reinforcement	Ø8 mm bars	Spaced at 150 mm centers (Ø8-150)

While the internal reinforcement can corrode over time, the steel plate itself is galvanized and thus largely protected from corrosion. The zinc coating acts as both a barrier and a sacrificial layer, corroding preferentially if exposed to corrosive elements. Even if minor scratches or surface damage occur, the underlying steel remains shielded. Since the slab is designed for three 50-year life cycles, periodic inspections and maintenance are essential. Fortunately, the plate remains accessible, allowing for additional protective coatings if needed. This measure ensures that, despite potential corrosion in the embedded reinforcement, the galvanized plate remains effectively safeguarded [65].

Detailed calculations for the deep deck composite slab, including the design of the steel decking, the concrete topping, and the composite action between the two materials, are provided in Appendix C. The corresponding Excel calculations for this slab are available in Appendix E. Figures 3.5 and 3.6 show the side and front views of the deep deck composite slab, illustrating the steel sheeting profile, the concrete topping, and the reinforcement arrangement.

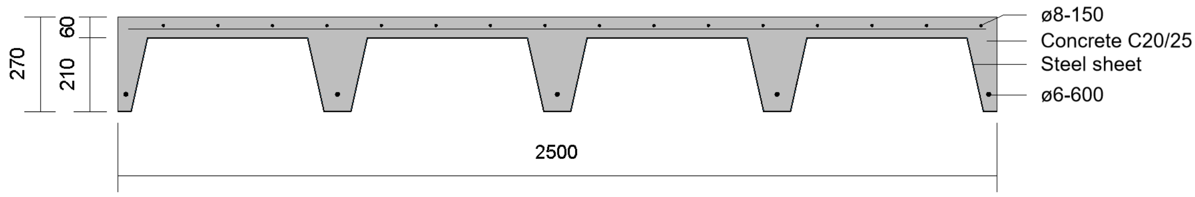


Figure 3.5: Deep Deck Composite Slab Side View

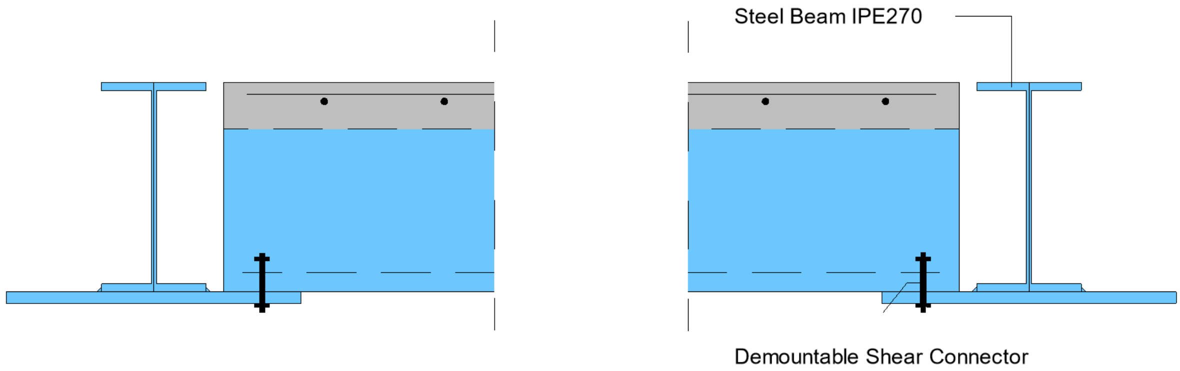


Figure 3.6: Deep Deck Composite Slab Front View

3.5. Reuse Considerations for Floor Systems

The considerations for reuse include compressive strength reduction and steel reinforcement corrosion. For the cast-in-situ slab, these degradation mechanisms are calculated for only one life cycle, as this slab adheres to a linear building economy model and is not reused. The effects of these degradation mechanisms are reflected in the governing failure mode, which is the bending moment. The impacts on other failure modes, such as shear force and deflection, are minimal as expected. Deflection is primarily dependent on the bending stiffness of the slab and is not influenced by the reinforcement or concrete strength. While shear force depends on both factors, the impact is limited. The results confirm these expectations. A summary of the unity checks for these failure modes under both compressive strength reduction and steel corrosion is provided in Table 3.10 and Table 3.12 respectively.

The bending moment remains the governing failure mode. The unity checks for compressive strength reduction and corrosion by carbonation at the end of the life cycle are 0.82 and 0.85, respectively.

For the hollow core slab and the deep deck composite slab, the circular building economy principle is applied. Consequently, strength reduction and corrosion progress over multiple life cycles. The initial design unity check is calculated at the start of the life cycle (t_0), with checks performed at the end of each subsequent life cycle: t_1 (end of life cycle 1), t_2 (end of life cycle 2), and t_3 (end of life cycle 3).

Calculations in Appendix F demonstrate that corrosion by carbonation affects the effective reinforcement area. For the deep deck composite slab, this effect remains within acceptable limits, enabling the slab to maintain structural integrity over three life cycles. This is due to the minimal reinforcement required for this slab, facilitated by the presence of the steel sheet. At the end of the last life cycle, the unity check (U.C.) is 0.88. Similarly, the compressive strength reduction remains below critical limits, with a U.C. of 0.78.

For the hollow core slab, the effect of compressive strength reduction also stays within acceptable limits, with a U.C. of 0.82. However, the effect of corrosion is more significant. Additional measures are required for the second and third life cycles, as the U.C. increases to 1.01 and 1.17 for t_2 and t_3, respectively.

To maintain structural integrity at the end of life, several intervention techniques can be applied. These techniques are discussed in Chapter 2.4. For this study, the selected intervention technique is steel plate bonding, as detailed in Chapter 2.4. Material quantities for the additional reinforcement were determined through calculations to ensure the U.C. remains below 1.0. The environmental impact of the additional materials was also calculated and included in the total environmental impact for the relevant life cycles.

3.6. Material Quantities

The material quantities for the design of the three slab systems, cast in-situ concrete slab, hollow core slab, and deep deck composite slab, have been calculated for the situation discussed in Chapter 3.1. An overview of the material quantities is given in Table 3.8.

For the cast in-situ concrete slab, the design requires 360.0 kg/m^2 of concrete and 6.17 kg/m^2 of main reinforcement. This slab, being the most traditional design, reflects the highest concrete volume among the three systems due to its solid construction, while the reinforcement quantity remains relatively low compared to the other systems.

The hollow core slab is designed to reduce material usage while maintaining structural integrity. It requires 252.15 kg/m^2 of concrete, which is significantly lower due to the hollow sections. The reinforcement includes 1.71 kg/m^2 of main reinforcement and 1.54 kg/m^2 of prestressed tendons, bringing the total reinforcement weight to 3.25 kg/m^2. This reduction in concrete weight demonstrates the efficiency of the hollow core design, while the inclusion of prestressed tendons ensures sufficient strength and durability.

The deep deck composite slab incorporates both concrete and steel for composite action, resulting in unique material requirements. The concrete quantity is 242.40 kg/m^2, slightly lower than the hollow core slab, and the main reinforcement weight is 0.37 kg/m^2, the lowest among all systems. Additionally, the steel sheet contributes 13.0 kg/m^2, which plays a significant role in the structural behavior of this slab. This configuration highlights the difference in material composition, with reduced concrete usage balanced by the inclusion of structural steel.

Table 3.8: Material Quantities per Square Meter for Different Slab Types

Quantity in [kg/m^2]	**Slab 1**	**Slab 2**	**Slab 3**
Concrete	360.00	252.15	242.40
Reinforcement	6.17	1.71	0.37
Tendons	-	1.54	-
Steel Sheet	-	-	13.0

These calculated material quantities provide a clear basis for comparing the resource requirements of each slab type under the conditions discussed in Chapter 3.1. The analysis is critical for evaluating both the structural and environmental performance of the floor systems.

3.7. Summary of Design Results

This section presents the results of the structural calculations for the three floor systems, focusing on the unity checks (U.C.) for bending moment, shear force, and deflection. The unity check is a ratio of the design action effect to the design resistance, where a value less than or equal to 1.0 indicates that the design meets the required performance criteria.

3.7.1. Initial Design Unity Checks

The initial design considers the performance of each floor system at the start of the first life cycle (t_0), without any degradation factors. The calculated unity checks for bending moment, shear force, and deflection are summarized in Table 3.9.

Table 3.9: Initial Unity Checks for Bending Moment, Shear Force, and Deflection

#	Slab Type	U.C. (Bending)	U.C. (Shear)	U.C. (Deflection)
1	Cast In-Situ Concrete Slab	0.78	0.40	0.38
2	Hollow Core Slab	0.82	0.15	0.46
3	Deep Deck Composite Slab	0.80	0.46	0.53

As shown in Table 3.9, all slabs have unity checks well below 1.0 for all failure modes, indicating that they meet the structural requirements with a margin of safety. Bending moment is confirmed to be the governing failure mode for all slabs, as anticipated in the design methodology. The shear force and deflection unity checks are significantly lower, suggesting that these failure modes are not critical under the given loading conditions.

3.7.2. Effects of Compressive Strength Reduction

The impact of compressive strength reduction is evaluated for each slab at the end of its life cycle. The unity checks considering compressive strength reduction are calculated and presented in Table 3.10.

Table 3.10: Unity Checks Considering Compressive Strength Reduction Over Life Cycles

Time	Slab 1			Slab 2			Slab 3		
	BM	SF	Defl	BM	SF	Defl	BM	SF	Defl
LC1	0.782	0.403	0.380	0.817	0.146	0.288	0.803	0.460	0.528
LC2	-	-	-	0.817	0.176	0.304	0.803	0.502	0.534
LC3	-	-	-	0.817	0.213	0.319	0.803	0.547	0.539

The results indicate that the unity checks remain largely unchanged when considering compressive strength reduction. This is because the bending moment capacity of reinforced concrete slabs is predominantly governed by the tensile capacity of the steel reinforcement (F_s) rather than the compressive strength of the concrete (F_c). In design practice, the steel reinforcement is intended to yield before the concrete reaches its compressive strength, promoting ductile failure modes.

When the compressive strength of the concrete reduces, the compressive force in the concrete (F_c) also reduces. However, since the compressive force is typically much higher than the tensile force in the steel (F_s) due to the lever arm effect, the reduction in F_c does not significantly affect the bending moment capacity. Therefore, the compressive strength reduction determined in Chapter 2.2 does not adversely impact the bending moment capacity of any of the slabs over 150 years.

As shown in Figure 3.7, the stress diagram illustrates how the forces are distributed in each slab. The governing failure force values, considering the reduced compressive strength, are presented in Table 3.11. These results further support the conclusion that the bending moment capacity remains largely unaffected by the reduction in compressive strength.

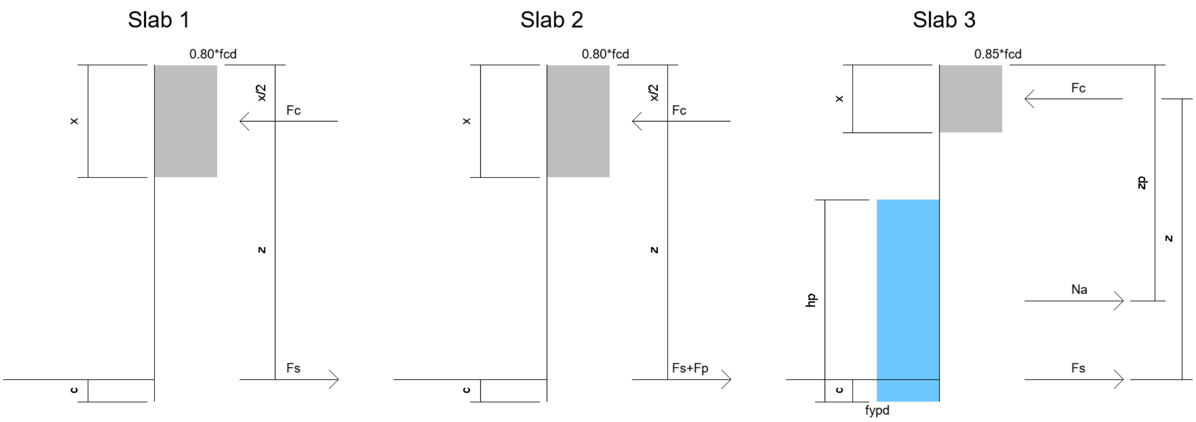


Figure 3.7: Stress Diagram for Each Slab

Table 3.11: Governing Failure Force Considering Reduced Compressive Strength

Slab	f_c [MPa]	F_c [kN]	F_s [kN]	$F_{governing}$ [kN]
Slab 1	20.0	597.3	341.5	341.5
	15.4	460.0	341.5	341.5
	11.9	354.2	341.5	341.5
Slab 2	20.0	731.1	270.9	270.9
	15.4	563.0	270.9	270.9
	11.9	443.5	270.9	270.9
Slab 3	20.0	1381.0	145.7	145.7
	15.4	1063.4	145.7	145.7
	11.9	818.8	145.7	145.7

Shear capacity, which is directly influenced by the compressive strength of the concrete, experiences a slight reduction. However, the unity checks for shear force remain well below 1.0, indicating that shear does not govern the design and remains within acceptable limits.

Deflection is not directly affected by the compressive strength reduction. Deflection is primarily dependent on the bending stiffness of the slab, which is a function of the modulus of elasticity (E) and the moment of inertia (I). Although the modulus of elasticity of concrete is correlated with its compressive strength, the reduction in compressive strength results in only a minimal change in E. Consequently, the effect on deflection is negligible for all slabs.

In conclusion, the effect of compressive strength reduction is determined to have an insignificant influence on the slab designs over multiple life cycles. The slabs maintain their structural integrity and continue to meet the design requirements despite the reduction in concrete compressive strength. Therefore, compressive strength reduction does not necessitate any design modifications or interventions for the slabs over the evaluated life cycles.

3.7.3. Effects of Corrosion

The impact of reinforcement corrosion due to carbonation is assessed separately. The unity checks, considering the reduction in effective reinforcement area, are calculated and shown in Table 3.12.

Table 3.12: Unity Checks Considering Reinforcement Corrosion Over Life Cycles

Time	Slab 1			Slab 2			Slab 3		
	BM	SF	Defl	BM	SF	Defl	BM	SF	Defl
t_0	0.782	0.403	0.380	0.817	0.146	0.288	0.803	0.460	0.528
t_1	0.816	0.403	0.380	0.872	0.147	0.288	0.811	0.471	0.528
t_2	-	-	-	1.012	0.150	0.288	0.834	0.507	0.528
t_3	-	-	-	1.188	0.154	0.288	0.864	0.577	0.528

The results show that reinforcement corrosion has a more pronounced effect on the structural capacity, especially for the hollow core slab. The cast in-situ slab is designed for only one life cycle and, therefore, is not significantly exposed to carbonation-induced corrosion, as its service life is limited to 50 years. In contrast, both the hollow core slab and the deep deck composite slab are evaluated over three life cycles of 50 years each. The key difference lies in their structural reliance: the hollow core slab depends heavily on reinforcement and prestressing tendons, incorporating higher quantities of both. In comparison, the deep deck composite slab requires less reinforcement and benefits more from the composite action between the steel sheeting and the concrete, as shown by the material quantities in Table 3.8. This distinction explains why the hollow core slab experiences a more significant reduction in capacity due to corrosion, ultimately exceeding the unity check of 1.0 in later life cycles.

At the end of the second life cycle (t_2), the unity check for the hollow core slab exceeds 1.0, indicating that the bending moment demand surpasses the reduced capacity due to corrosion. By the third life cycle (t_3), the unity check increases further, suggesting that the hollow core slab would not meet the structural requirements without intervention.

The deep deck composite slab maintains unity checks below 1.0 throughout the three life cycles, although there is a gradual increase due to corrosion effects. This resilience is attributed to the minimal reinforcement required for this slab and the contribution of the steel decking to the overall structural capacity.

Although deep deck composite slab's embedded reinforcement is subject to the same corrosion considerations as other slabs, the galvanized steel plate is excluded from these calculations. As explained in Section 3.4, its zinc coating provides both a protective and sacrificial layer, and any minor damage can be addressed through routine maintenance. Therefore, while reinforcement corrosion is accounted for, the steel plate remains safeguarded from similar corrosive degradation [65].

3.7.4. Discussion of Results

The analysis demonstrates that while all slabs perform adequately in the initial design, the introduction of degradation factors affects their structural performance differently over multiple life cycles:

- Cast In-Situ Concrete Slab: Designed for a single life cycle, this slab demonstrates acceptable unity checks, all remaining below 1.0 and thus indicating sufficient capacity. Since this slab serves as the reference case within a linear building economy, it is minimally affected, as shown in Table 3.10 and Table 3.12, and remains within acceptable limits.
- Hollow Core Slab: Compressive strength reduction alone does not critically impact the slab's performance. However, reinforcement corrosion significantly affects the bending capacity in subsequent life cycles. Without intervention, the slab's capacity becomes insufficient after the second life cycle, as indicated by unity checks exceeding 1.0. Therefore it needs an intervention measure. This will be discussed in section 3.7.5.
- Deep Deck Composite Slab: The slab demonstrates robustness against both degradation factors over three life cycles. The unity checks remain below 1.0, and the structural integrity is maintained, largely due to the presence of the steel decking and the reduced reliance on reinforcement bars.

3.7.5. Intervention Measures

For the hollow core slab, intervention measures are necessary to maintain structural integrity in the second and third life cycles due to the significant impact of reinforcement corrosion. The selected intervention technique is steel plate bonding, which involves attaching steel plates to the tension face of the slab to enhance its bending capacity.

While various strengthening options exist (such as FRP strengthening, post-tensioning, or concrete jacketing) as mentioned in Chapter 2.4, steel plate bonding was selected for several practical reasons. First, it has a well-documented track record of effectively restoring flexural capacity in slabs [42, 43, 44]. Second, it is relatively straightforward to implement, requiring only standard steel plates, high-strength adhesives, and minimal specialized equipment [44]. Third, compared to other reinforcement methods, steel plate bonding saves both time and money, with lower installation costs making it a viable option [44]. Fourth, the technique's added material requirements (in this case, steel plates) are easier to quantify from an environmental impact perspective, aligning with the multi-life cycle assessment focus of this study. Finally, steel plate bonding can be combined with other interventions if necessary, offering flexibility for future repair or adaptation [41].

Calculations indicate that steel plates made of S275 grade steel, measuring 4 mm in thickness and 90 mm in width per meter of slab width, are required to restore the slab's bending capacity to acceptable levels. The addition of these steel plates effectively reduces the unity checks below 0.8, ensuring that the slab meets the structural requirements for bending moment in the subsequent life cycles. Figures 3.8 and 3.9 illustrate the side view and front view of the hollow core slab with the strengthening of the slab with the intervention technique steel plate bonding.

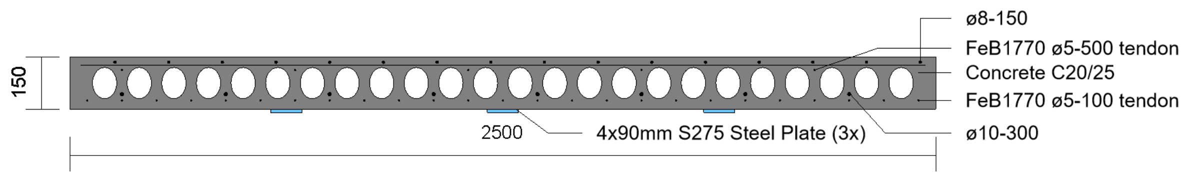


Figure 3.8: Hollow Core Slab With Intervention Technique Steel Plate Bonding Side View

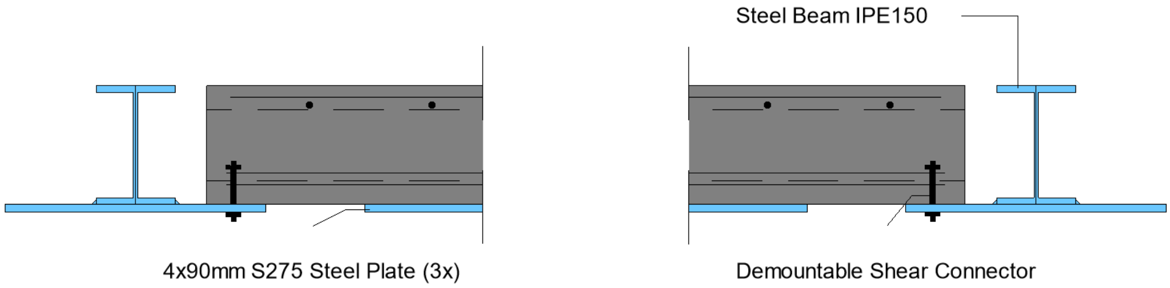


Figure 3.9: Hollow Core Slab With Intervention Technique Steel Plate Bonding Front View

The choice of a 4 mm plate thickness aligns with recommendations from previous studies, which suggest that the minimum plate thickness should not be less than 4 mm to avoid distortions during grit blasting and handling on site [66]. Thinner plates may be susceptible to damage or deformation during the installation process, compromising the effectiveness of the intervention.

The additional environmental impact associated with the use of these steel plates, which is equivalent to 2.36 kg of steel per square meter, will be calculated and included in the total environmental impact assessment for the relevant life cycles. This will be discussed in detail in Chapter 5.1, ensuring that the environmental benefits of reusing the slab are accurately reflected, accounting for the resources required for the intervention.

4
Parametric Model

This chapter presents the development of a parametric model for structural analysis using Rhino, Grasshopper [67], and Karamba3D [68]. The model enables flexible design adjustments and real-time analysis of structural behavior under various conditions. By integrating parametric design principles with advanced computational tools, the model facilitates efficient exploration of design alternatives and optimization of structural elements. The goal is to create an interactive platform that simulates the performance of floor systems under different loads, materials, and support conditions, providing valuable insights for both design and analysis.

4.1. Model Development

The development of the parametric model involves several key steps: initial setup and geometry definition, mesh conversion to structural elements, material assignment, definition of support conditions, load application, incorporation of material reduction factors to simulate degradation or design variations, and implementation as an interactive digital tool.

An essential aspect of this parametric model is its role as an accessible and interactive tool created using Karamba3D and Grasshopper. It allows exploration of how various changes, such as different grid sizes and materials, influence structural outcomes like deflection and stress distribution. By enabling real-time adjustments and providing visual feedback, the tool aids in understanding the impact of these variables on the overall performance of the floor systems. The following subsections detail each step of the model development process.

4.1.1. Overview

The parametric model is built using Grasshopper, a visual programming interface within Rhino, which connects various design and analysis components. Karamba3D, a structural analysis tool, is integrated into the workflow to simulate structural behavior and calculate forces, displacements, and stresses. This setup provides an interactive platform for optimizing structural elements and evaluating performance under different loads and support conditions. An overview of the Grasshopper model is depicted in Figure 4.1.

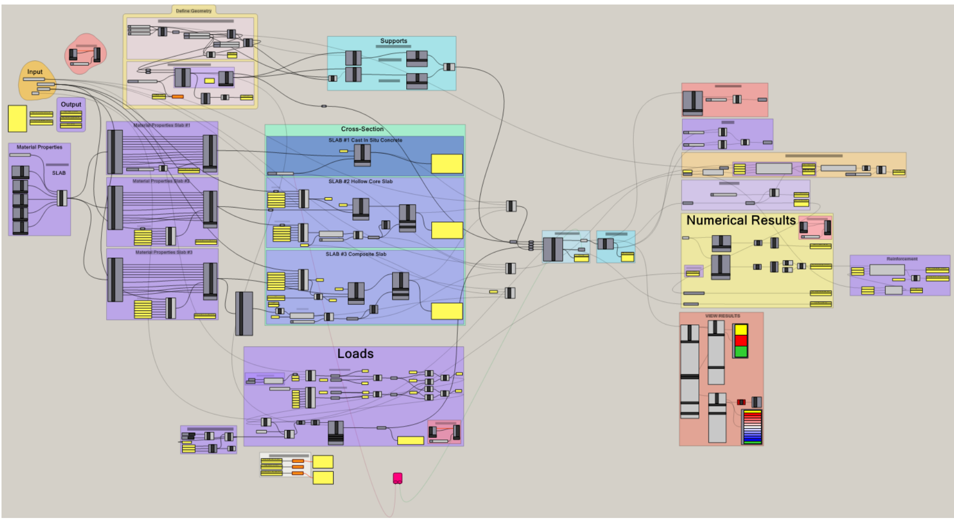


Figure 4.1: Overview Grasshopper Model

4.2. Initial Setup and Geometry Definition

The modeling process begins with establishing a foundational point in Grasshopper, which serves as the anchor for the entire model. This initial point ensures that any changes to the model's parameters automatically update the geometry, embodying the principles of parametric design. The grid size is defined with dimensions of 5.4 meters by 2.5 meters, reflecting typical structural spans in office buildings and selected based on specific design requirements. Using these dimensions, a mesh is created by connecting the four corner points, forming the basic outline of the slab model, as shown in Figure 4.2.

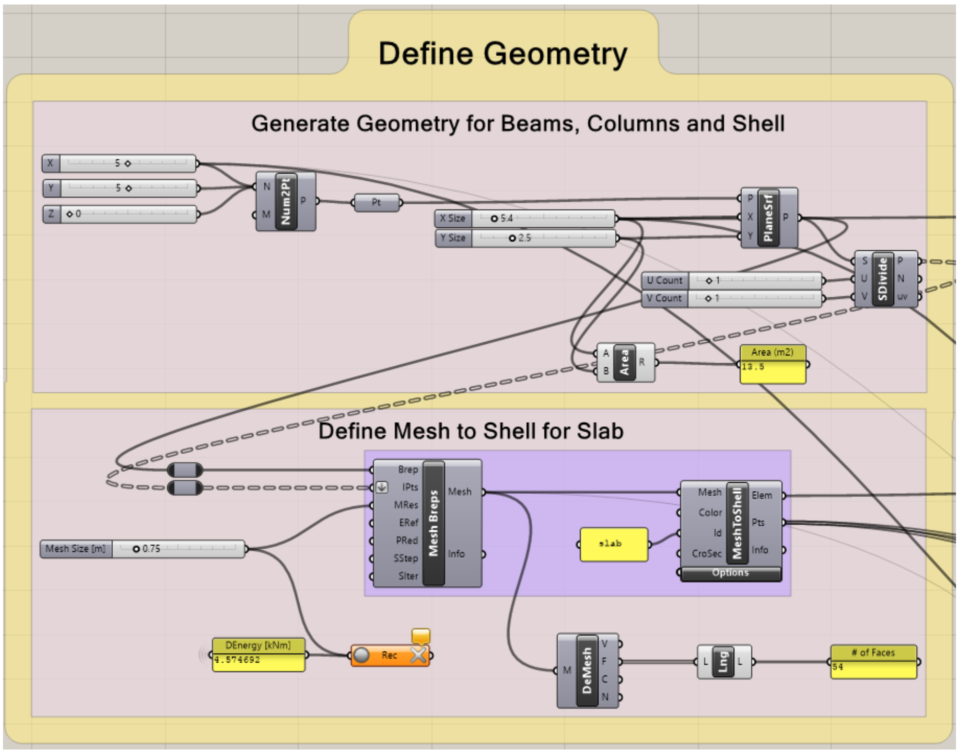


Figure 4.2: Geometry and Mesh Definition

4.2.1. Mesh Conversion to Structural Elements

After defining the mesh, it is converted into a structural shell element that accurately represents the slab. The mesh-to-shell component in Grasshopper is utilized for this purpose, enabling a seamless transformation suitable for finite element analysis. To enhance the structural realism of the model, beams are generated along the two primary edges of the slab using dedicated Grasshopper components. These beams provide additional support and rigidity, ensuring that the model behaves as expected under load conditions. This setup effectively simulates the slab and its supporting elements within the model.

4.2.2. Material Assignment

Material properties are assigned to the key structural element using the material selection components in Grasshopper. Concrete is assigned to the slab, and steel is assigned to the beams, reflecting common construction practices and the materials' inherent suitability for their respective structural roles. Filters are applied to allow easy adjustments of material strength parameters, enabling exploration of different scenarios such as varying concrete grades or steel strengths. This flexibility is crucial for assessing the impact of material choices on the overall performance of the structure. Figure 4.3 illustrates the material assignment process.

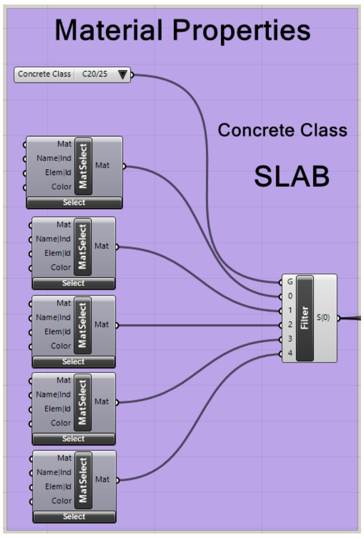


Figure 4.3: Material Properties

4.2.3. Homogenization and Modeling of Slabs in Karamba3D

Due to the limitations of Karamba3D, which primarily supports standard uniform sections, modeling slabs with complex geometries or composite materials necessitates an alternative approach. The hollow core slab and the deep deck composite slab, which feature complex cross-sectional shapes, present significant challenges for direct modeling within the software.

For the deep deck composite slab, which consists of two different materials, the effective bending stiffness is homogenized into a uniform value. This process simplifies the complex interactions between the materials by calculating an equivalent bending stiffness that reflects the combined properties of the slab's components. According to the method outlined in [69], the homogenized bending stiffness $(EI)_{\text{hom}}$ for this slab is determined using the formula:

$$(EI)_{\text{hom}} = \sum_i E_i I_i$$

where E_i represents the modulus of elasticity and I_i the moment of inertia for each layer i of the slab.

This approach allows the deep deck composite slab to be modeled as an equivalent uniform structure with consistent bending stiffness throughout. Utilizing homogenized bending stiffness streamlines the modeling process and boosts computational efficiency, ensuring accurate predictions of the slab's behavior under various loading conditions within the capabilities of the software.

For the hollow core slab, which consists of a single material but lacks a uniform standard cross-section, and now for the deep deck composite slab, after homogenization, each slab is modeled as a uniform cross-section. The thickness h of these slabs is calculated based on the actual moment of inertia using the formula:

$$h = \left(\frac{12 \cdot I}{b}\right)^{\frac{1}{3}}$$

where I is the moment of inertia and b is the base width of the slab.

The cast in-situ concrete slab, being uniformly consistent in material properties throughout its entire structure, can be modeled directly in Karamba3D without the need for homogenization.

4.2.4. Support Conditions

Defining the support conditions is critical, as it directly influences the structural response under applied loads. The slab is modeled as simply supported, with the edges constrained in all translational directions (X, Y, and Z axes) while allowing rotational movement. This setup simulates a realistic structural configuration where the slab is free to rotate but restrained from any translational motion, providing a clear understanding of its performance under basic support scenarios. The choice of simply supported conditions facilitates analysis and interpretation of the results. Figure 4.4 shows the support conditions applied in the model.

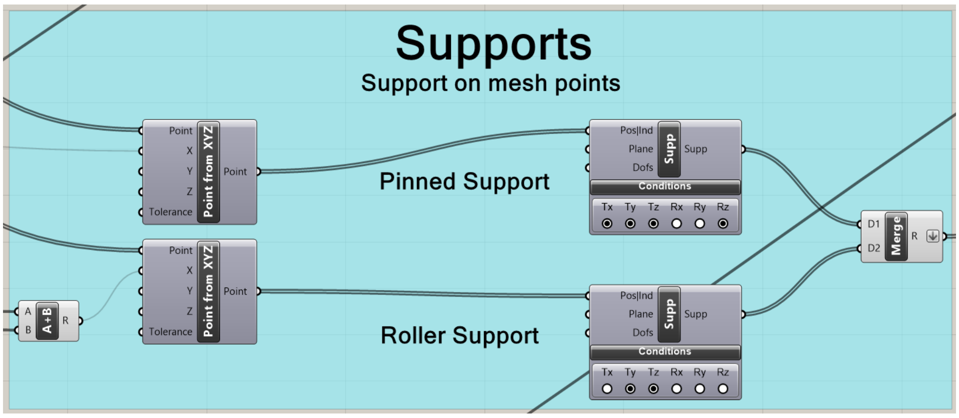


Figure 4.4: Support Conditions

4.2.5. Load Application

The loads applied to the model are divided into two main categories: self-weight and live load. The self-weight is automatically calculated using the loads component when gravity is selected as the type of load. Gravity affects all active elements in the structural model where the specific weight gamma is non-zero. The gravity vector defines the direction of the gravitational force, with a vector of length one corresponding to Earth's gravity. In the context of SI units, Karamba3D assumes a gravitational acceleration value of 10 m/s². The live load is created using the mesh load constant component. Multiple inputs are configured to allow easy switching between different load functions, such as the office load of 2.5 kN/m² according to Eurocode and the National Annex. For the purpose of this report, an office load is applied.Figure 4.5 illustrates the load application setup.

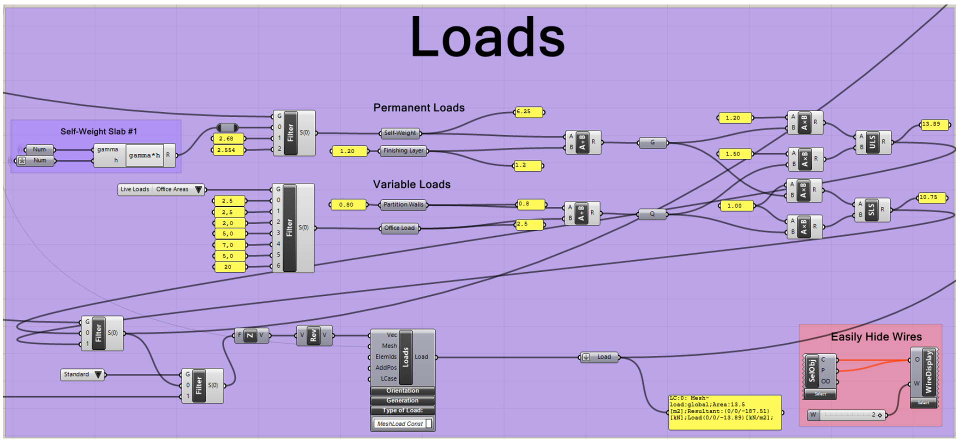


Figure 4.5: Load Cases

4.2.6. Special Considerations

To simulate scenarios such as material degradation over time or design considerations requiring lower safety factors, a reduction factor slider is incorporated into the model. This slider is linked to critical material properties, including the modulus of elasticity, compressive strength, and tensile strength. By adjusting these reduction factors, the model can analyze the impact of reduced material properties on structural performance, providing valuable insights for design optimization and risk assessment. This feature enhances the model's capability to simulate various real-world conditions and design strategies. Figure 4.7 shows the implementation of material reduction factors.

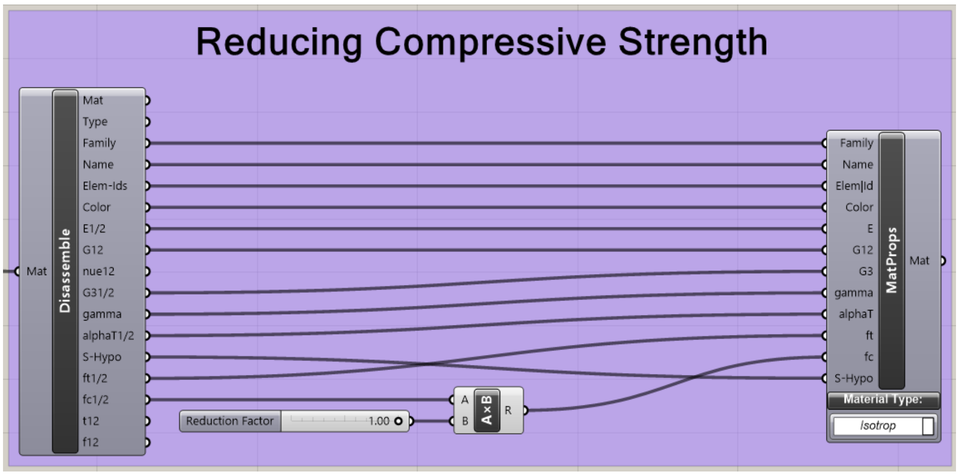


Figure 4.6: Reduction Factor on Material Properties

4.2.7. Life Cycle Assessment (LCA)

The model also incorporates a Life Cycle Assessment (LCA) to evaluate the environmental impact of the slab. This assessment calculates key metrics such as Global Warming Potential (GWP), embodied energy, and material-related emissions. These calculations are based on input data for material quantities derived from the design and environmental data sourced from GPR Material databases. The integration of LCA ensures that environmental considerations are part of the decision-making process alongside structural performance.

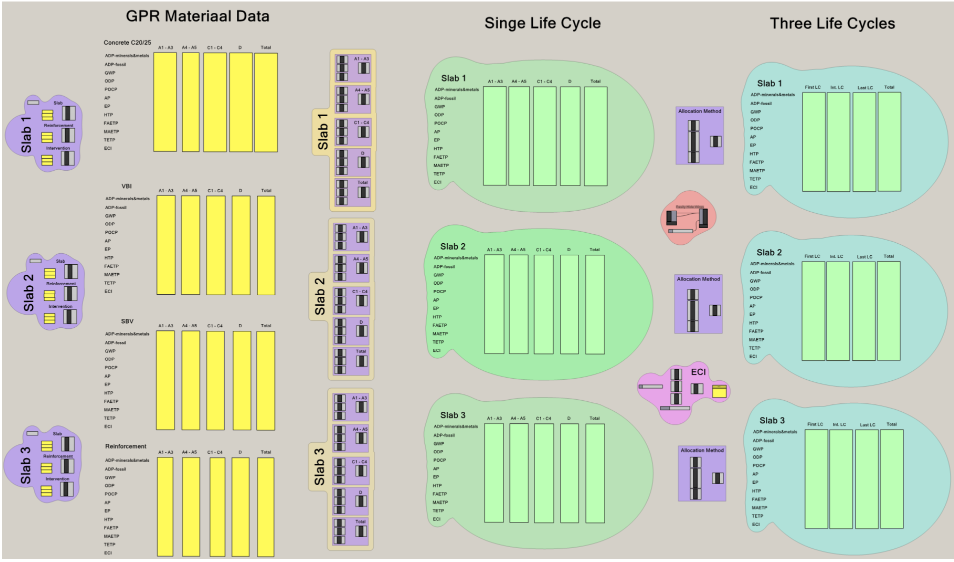


Figure 4.7: Life Cycle Assessment

4.3. Analysis and Results

This section presents the findings from the parametric model, emphasizing the structural analysis of the slabs. Core aspects of the analysis include mesh sensitivity studies, deflection, normal stresses, and bending moments, complemented by a detailed discussion of the results. Furthermore, the integration of Excel-based calculations for life cycle assessment (LCA) and structural parameters significantly enhances the model's capabilities.

4.3.1. Mesh Sensitivity Analysis

Selecting an optimal mesh size in finite element analysis is crucial for balancing computational efficiency with the accuracy of results. This balance is assessed by evaluating deformation energy, which quantifies the energy absorbed by a structure when it deforms under load.

Figure 4.8 demonstrates the impact of mesh size on deformation energy. As depicted, decreasing the mesh size results in increased deformation energy until it reaches a plateau.

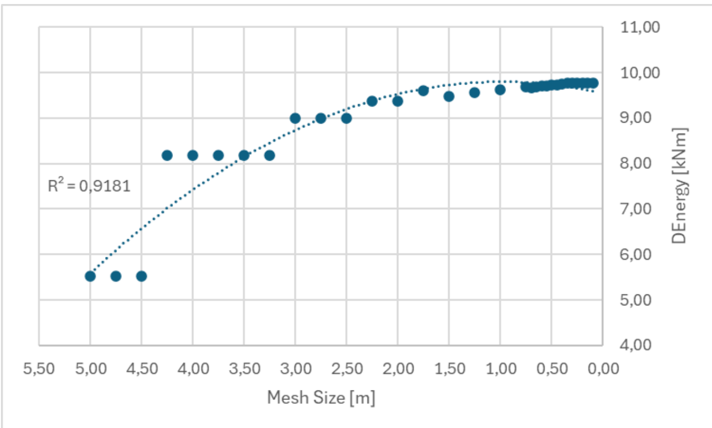


Figure 4.8: Relationship Between Mesh Size and Deformation Energy

The analysis shows that a mesh size of 0.3 meters effectively balances computational demands with the precision of deformation energy calculations. Reducing the mesh size further yields only marginal improvements in accuracy but requires significantly more computational resources and time. Consequently, a mesh size of 0.3 meters is selected.

4.3.2. Numerical Results

The Karamba model provides several structural analysis outputs, including deflection, bending moment, and normal stresses values that the slab must resist. The input parameters are configured to enable switching between different slab types and load scenarios, such as ULS or SLS, allowing quick evaluation of the corresponding outcomes.

Deflection

The deflections of the three slabs are visualized in Figures 4.9, 4.10, and 4.11, corresponding to slabs 1, 2, and 3, respectively. Each visualization is accompanied by a legend to indicate the deflection values across the length of the slab.

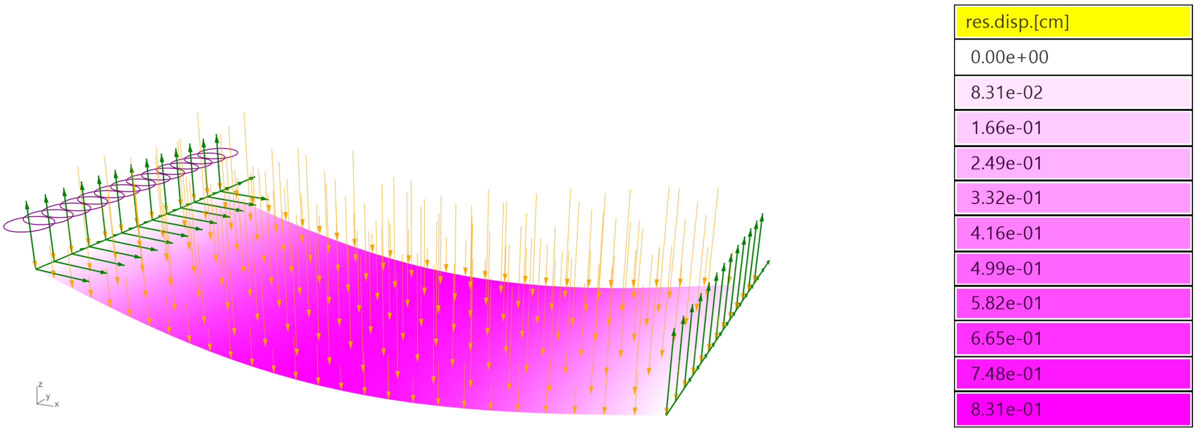


Figure 4.9: Deflection Visualization of Simpy Supported Slab 1 in Karamba

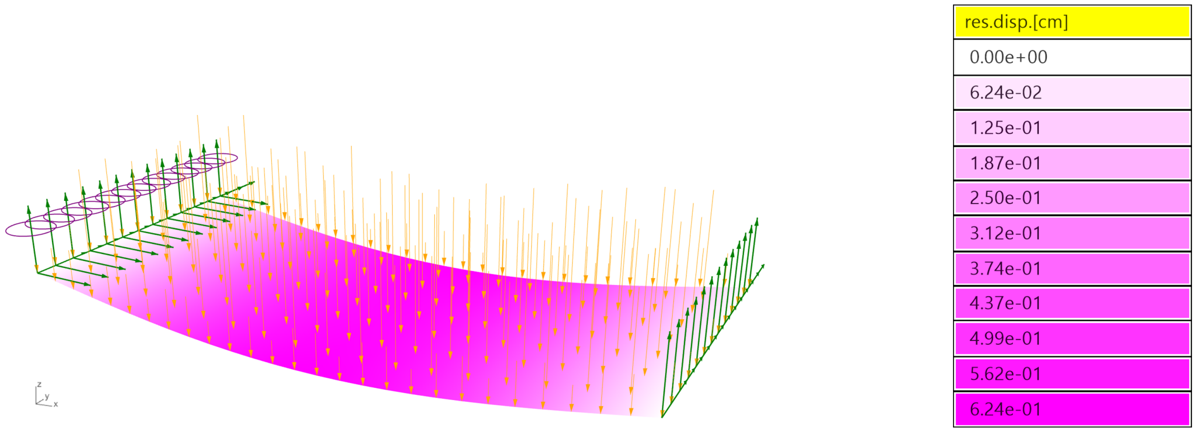


Figure 4.10: Deflection Visualization of Simpy Supported Slab 2 in Karamba

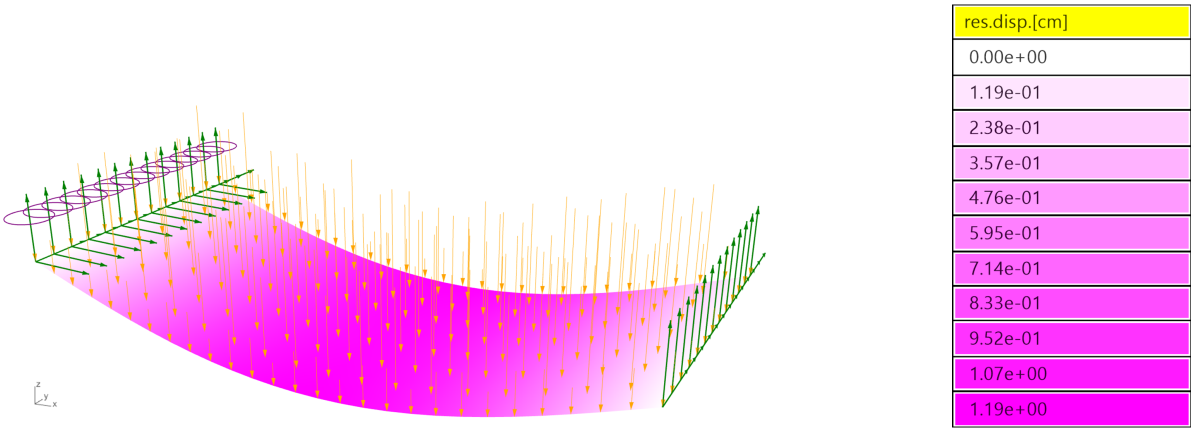


Figure 4.11: Deflection Visualization of Simpy Supported Slab 3 in Karamba

Table 4.1 presents a comparison between the analytical model (AM) and numerical model (NM) deflection results for all three slabs. The percentage differences between the models are minimal, falling within acceptable limits. This indicates that the numerical model is well-validated with respect to deflection analysis.

Table 4.1: Comparison of analytical model and numerical model deflections with percentage differences for each slab

Slab	Deflection (mm)		
	AM	NM	% Difference
Slab 1	8.21	8.31	1.18%
Slab 2	6.21	6.24	0.44%
Slab 3	11.41	11.88	3.97%

Bending Moment

The bending moments of the three slabs are compared in Table 4.2, showing the analytical model (AM) and numerical model (NM) results. The percentage differences between the models are minimal and consistently under 2%, validating the accuracy of the numerical model in predicting bending moments.

Table 4.2: Comparison of analytical model and numerical model bending moments with percentage differences for each slab

Slab	Bending Moment (kNm)		
	AM	NM	% Difference
Slab 1	30.07	30.57	1.63%
Slab 2	25.39	25.81	1.62%
Slab 3	25.35	25.77	1.64%

Additionally, the calculations performed in Excel for the life cycle assessment (multi-LCA), bending moment resistance, shear force, allocation method, and sensitivity analysis have all been manually incorporated into the Grasshopper file. This integration ensures that the Grasshopper file is a fully standalone tool, capable of independent analysis, while the Excel file also remains a standalone resource for similar evaluations.

Normal Stresses

The normal stresses of the three slabs are visualized in Figures 4.12 and 4.13, corresponding to slabs 1 and 2. Each visualization is accompanied by a legend to indicate the normal stress values at the outer face of the slab. For slab 3, the normal stresses are not shown because an alternative method had to be used for modeling the deep deck composite slab. As explained in Chapter 4.2.3, slab 3 was modeled as a uniform section, which assumes the neutral axis is at the center. However, in reality, the neutral axis is not at the center, leading to inaccurate normal stresses at the outer face. Therefore, they are neglected in the comparison.

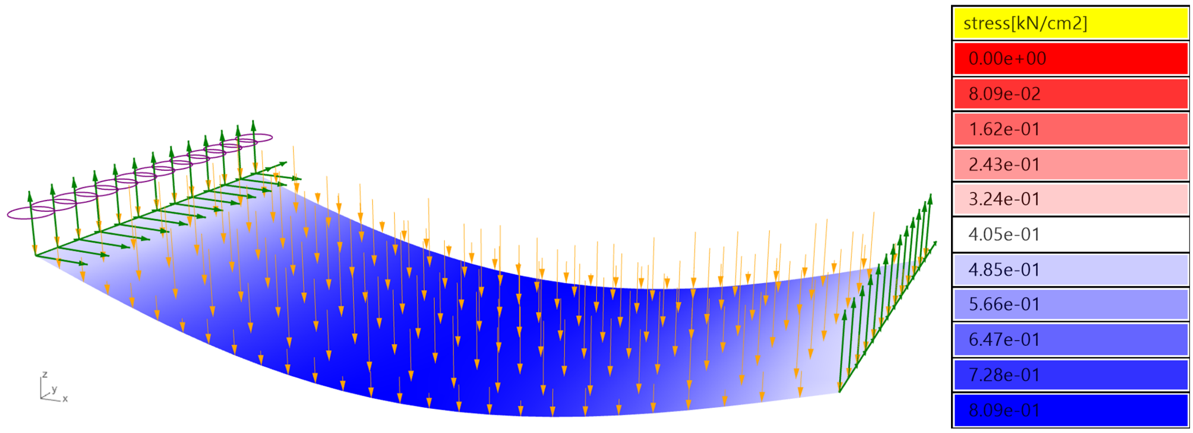


Figure 4.12: Normal Stresses Visualization of Simpy Supported Slab 1 in Karamba

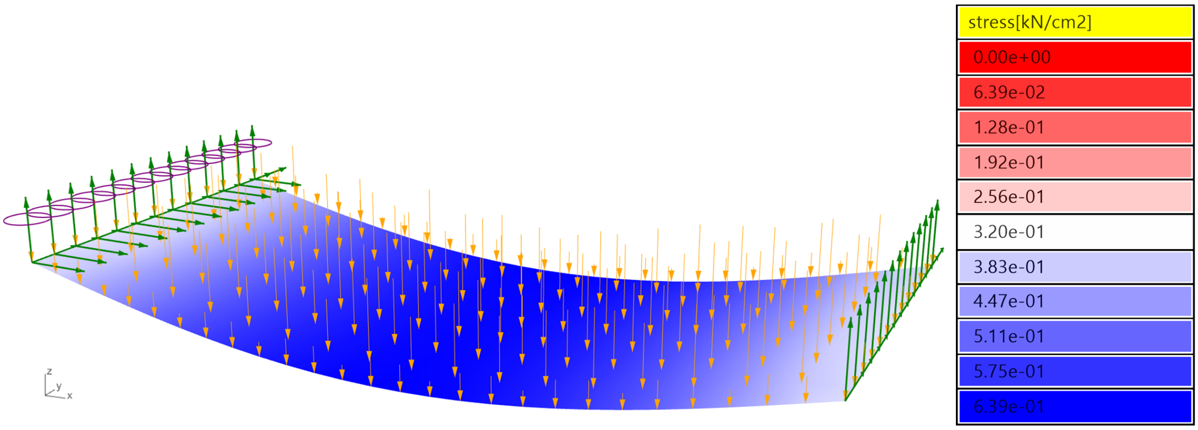


Figure 4.13: Normal Stresses Visualization of Simpy Supported Slab 2 in Karamba

Table 4.3 presents a comparison between the analytical model (AM) and numerical model (NM) normal stress results for slabs 1 and 2. The percentage differences between the models are minimal for slab 1, while slab 2 shows slightly larger discrepancies, though still within acceptable limits.

Table 4.3: Comparison of analytical model and numerical model normal stresses with percentage differences for each slab

Slab	Normal Stress (MPa)		
	AM	**NM**	**% Difference**
Slab 1	8.02	8.09	0.88%
Slab 2	6.18	6.39	3.27%
Slab 3	-	-	-

4.3.3. Discussion of Findings

The comparison between the results of the analytical model (AM) and the numerical model (NM) demonstrates that the Karamba-based parametric model provides reliable predictions of structural behavior. The minor differences observed, such as the percentage discrepancies in deflection, normal stresses, and bending moments, fall within acceptable engineering limits and are consistent with typical variations between numerical and analytical methods.

The deflection results are well-aligned, with a maximum difference of 3.97% for slab 3, validating the numerical model's ability to predict deformations accurately. For normal stresses, variation remain low for slabs 1 and 2, with a slightly higher difference of 3.27% for slab 2, which may be attributed to minor differences in load distribution or material assumptions. For slab 3, the principal stresses were neglected due to modeling simplifications. These simplifications, discussed in Chapter 4.2.3, involved modelling the deep deck composite slab as a uniform section with the neutral axis at the center, which does not reflect the real physical behavior of the slab.

The bending moment results show consistently minimal differences, with all discrepancies under 2%, further validating the model's accuracy. These findings suggest that the Karamba model is a robust tool for structural analysis.

Additionally, the integration of Excel-based calculations, including the multi-LCA, bending moment resistance, shear force, allocation method, and sensitivity analysis, into the Grasshopper file significantly enhances the utility of the model. This ensures that the Grasshopper file functions as a fully independent and standalone tool, capable of conducting comprehensive structural and environmental assessments without reliance on external software. At the same time, the Excel file remains a standalone resource, offering users flexibility in choosing their preferred workflow.

The flexibility of the model to adjust parameters such as grid size, material properties, support conditions, and loading scenarios, linked with its ability to provide both visual and numerical outputs, enables users to explore a wide range of structural configurations. This adaptability makes the model a valuable tool for both design optimization and structural assessment.

4.4. Conclusion

The study demonstrates that the parametric model developed in Karamba is a reliable and accurate tool for structural analysis, capable of predicting deflection, normal stresses, and bending moments within acceptable limits of accuracy. The integration of Excel-based calculations into the Grasshopper model further enhances its functionality, ensuring that the Grasshopper file operates independently while also providing flexibility through the standalone Excel workflow.

The parametric model's adaptability to changes in slab type, load conditions, and design scenarios, as well as its ability to incorporate advanced analyses such as sensitivity studies and allocation methods, makes it a versatile and efficient tool for structural engineering applications. The minor differences between the analytical and numerical results validate the model's reliability while acknowledging the limitations inherent to simplified assumptions, such as those applied to the deep deck composite slab (slab 3).

In conclusion, the parametric model provides an effective platform for analyzing and optimizing slab designs, supporting both structural safety and environmental performance. Its independence, flexibility, and accuracy make it a valuable tool for engineers, enabling them to explore a wide range of design scenarios and make informed decisions during the design process.

5
Environmental Impact

This chapter introduces the framework of Multi-Life Cycle Assessment (LCA) to evaluate the environmental impacts of various floor systems designed for steel-framed buildings over multiple life cycles. It begins by outlining the LCA process, focusing on goal and scope definition, data collection, and interpretation standards while addressing challenges related to data availability and methodological decisions.

The chapter explains the rationale behind this approach, outlines the key components of the framework, and provides a step-by-step guide for its application. This framework serves as a practical tool for engineers to assess the environmental performance of floor systems in real-world projects over extended life cycles.

5.1. Framework for Environmental Impact Analysis

This section introduces a framework for conducting a multi-life cycle environmental impact assessment of floor systems. Unlike traditional Life Cycle Assessment (LCA) methods, which typically focus on one or two life cycles, this framework provides a structured approach to assess the environmental impacts of materials over multiple reuse cycles. By capturing the long-term sustainability benefits of reusing floor systems, this methodology enables engineers and researchers to make more accurate and informed environmental assessments.

5.1.1. Goal and Scope Definition

In defining the scope for an environmental impact assessment, it is essential to establish clear system boundaries and specify a functional unit. The system boundaries outline which life cycle stages are included in the assessment, ensuring that all relevant environmental impacts are comprehensively and transparently evaluated. Defining a functional unit is equally important for enabling consistent comparisons across different systems. This unit serves as a reference point, facilitating the assessment of material use, construction methods, and sustainability strategies [70].

The system boundaries are structured around the life cycle stages, which encompass the various phases of a product's existence, from creation to disposal. According to EN standards (EN 15978 [71] and EN 15804 [47]), the life cycle stages for a building are as follows:

- **A1-A3 (Product Stage):** Raw material extraction and processing, transport to the manufacturer, and manufacturing.
- **A4-A5 (Construction Stage):** Transport to the building site and installation into the structure.
- **B1-B7 (Use Stage):** Use or application of the installed product, maintenance, repair, replacement, refurbishment, and operational energy and water use.
- **C1-C4 (End-of-Life Stage):** Deconstruction, demolition, transport to waste processing, waste processing for reuse, recovery and/or recycling, and disposal.

- **D (Beyond Life Cycle):** Reuse, recovery, and/or recycling potentials.

These stages facilitate a comprehensive understanding and assessment of environmental impacts throughout the entire lifecycle of a building. Figure 5.1 illustrates the life cycle stages within the system boundaries [72].

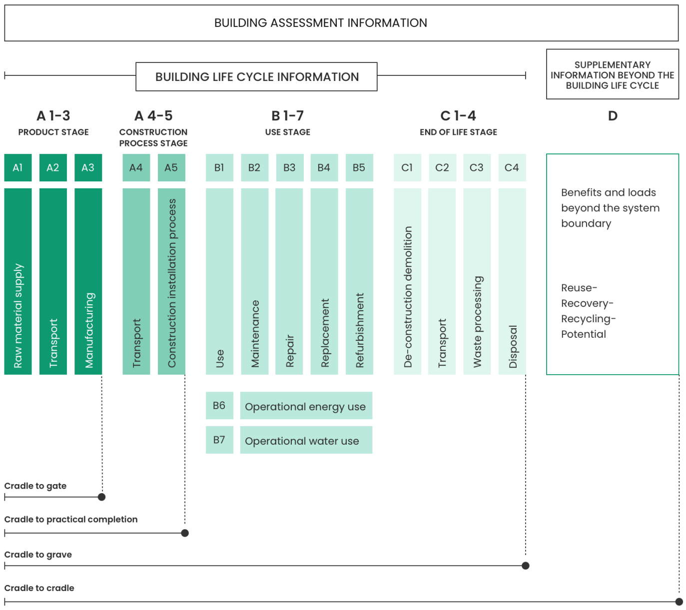


Figure 5.1: LCA System Boundary [72]

5.1.2. Material Data and Assessment Tools

Material Inventory for Environmental Assessment

A critical step in conducting environmental impact assessments is the creation of a comprehensive material inventory. This involves calculating the precise quantities of materials such as concrete, steel, insulation, and other building components, based on the specific designs of the floor systems or other elements under study. By establishing a consistent functional unit—such as one square meter of floor area, accurate comparisons can be made between different systems. This approach ensures that results are directly relevant to the environmental objectives of the project. Using a standardized functional unit helps normalize the data for comparative analysis and aligns with the requirements for detailed lifecycle impact calculations.

Tools and Data Sources for Environmental Assessment

The reliability of environmental impact assessments depends heavily on the quality of data and tools used. In the Netherlands, the Nationale Milieu Database (NMD) serves as the primary source of verified environmental data for building materials and products, ensuring compliance with the national sustainability standards established in the Dutch Building Decree [73].

Several tools validated by the NMD—including GPR Materiaal, MPG Toetshulp, Dubocalc, MRPI-MPG Tool, BCI Gebouw, Madaster MPG Tool, and MPGcalc—support detailed life cycle assessments of building components. These tools adhere to international standards such as ISO 14040 [74] and ISO 14044 [75]. By integrating with NMD data, these tools enable up-to-date and compliant assessments that are essential for achieving sustainability certifications and building permits. This integration ensures that environmental assessments are reliable and consistent with regulatory requirements.

Data Categories

The Nationale Milieu Database (NMD) classifies data into three categories—Category 1, Category 2, and Category 3—each representing a different level of data quality and reliability essential for accurate life cycle assessments (LCA) [76]:

- **Category 1 Data:** The highest quality data in the NMD, consisting of verified, proprietary information provided directly by manufacturers. This data undergoes rigorous testing and validation by NMD experts to ensure accuracy and representativeness. It is product-specific and accounts for actual production processes, material compositions, and associated environmental impacts.
- **Category 2 Data:** Industry-average data that is independently verified to reflect typical products or materials within a specific sector. Although less precise than Category 1, it offers a reliable approximation of environmental impacts when product-specific data is unavailable.
- **Category 3 Data:** Generic data used as a fallback when Categories 1 and 2 are not available. This data lacks the verification and precision of higher categories, resulting in higher uncertainty. A 30% markup is applied to environmental impact calculations using Category 3 data to account for potential underestimations.

5.1.3. Selection of Environmental Impact Categories

A robust framework for the comparative environmental assessment of floor systems should adhere to the EN 15804 standard [47], which underpins the Environmental Performance of Buildings (MPG) calculation in the Netherlands. Currently, Set A1 impact categories are mandatory for MPG assessments of new buildings, reflecting the established standard in practice. However, as of July 2025, the mandatory transition to Set A2 categories will incorporate updated scientific methodologies and refined environmental indicators.

Incorporation of the Shadow Pricing Method

Shadow pricing provides a monetary representation of environmental impacts, serving as a crucial tool for comparative assessments. By consolidating multiple environmental impacts into a single cost metric, shadow pricing enables a clear evaluation and comparison of floor systems. This framework integrates shadow pricing to calculate Environmental Cost Indicators (ECI) based on defined impact categories, ensuring a standardized and transparent approach to lifecycle environmental assessment. Consequently, environmental costs can be consistently compared across different systems and life cycle stages.

5.1.4. Number of Life Cycles

This study considers three distinct life cycles for assessing the environmental impact of floor systems: the first life cycle, an intermediate life cycle, and a final life cycle. A minimum of two life cycles is necessary to capture the reuse process, but to achieve a more comprehensive assessment, one intermediate life cycle is included. Literature indicates that the intermediate life cycle often incurs the least environmental impact, as the structure is reused with minimal intervention. By incorporating this intermediate stage, the analysis captures this aspect while allowing scalability for future studies considering additional intermediate life cycles.

Since slabs cannot be reused indefinitely, the analysis is limited to three life cycles. This approach provides a clear understanding of the cumulative environmental impacts across the structure's lifespan. Consistent allocation methods for environmental impacts across intermediate life cycles simplify the analysis without sacrificing the ability to extrapolate results to longer reuse scenarios. Thus, the three life cycles effectively represent the key stages of reuse and overall environmental performance.

5.1.5. Choosing an Allocation Method

Several allocation methods are available for distributing environmental impacts across different life cycles, particularly when assessing reused building components. Each method employs specific strategies to assign the environmental burden associated with these components, offering diverse ways to track and understand how impacts evolve over multiple use cycles.

Different approaches to evaluating the full life cycle impact of reused components rely on distinct assumptions and calculations regarding assessment boundaries and impact allocation. [77] provides a review of these methods, drawing insights from widely recognized standards, rating schemes, and relevant academic research. This review highlights how each approach manages impact distribution and its implications for environmental performance.

The ISO 14044 standard [75] mandates the selection of an impact allocation method but does not prescribe a specific approach, leaving the choice to the practitioner [78]. Among the various methods, the cut-off approach is one of the most commonly used. This study also adopts the cut-off method for evaluating environmental impacts, consistent with its widespread application and established use in the field [79].

The cut-off method allocates the environmental impacts from the production stage (A1–A3) to the initial use of a building component, while the impacts from the end-of-life phase (C1–C4) are assigned to the final use cycle. For intermediate life cycles, the method only includes impacts related to transportation and construction (A4–A5), usage (B1–B7), and reuse (D). This approach is designed to provide precise results by attributing impacts to the exact stage where they occur [77].

The environmental impact under the cut-off approach is calculated using the following equation:

$$EI = (1 - R_1) \cdot EI_P + EI_C + EI_U + (1 - R_2) \cdot EI_{EoL} + R_1 \cdot EI_R \quad (5.1)$$

where:

EI = Environmental impact
EI_P = Environmental impact of production
EI_C = Environmental impact of construction
EI_U = Environmental impact of use
EI_{EoL} = Environmental impact of end-of-life disposal
EI_R = Environmental impact of reuse
R_1 = Coefficient for the use cycle of the component, taking values 0 or 1
R_2 = Coefficient for the use cycle of the component, taking values 0 or 1

For the first use cycle: $R_1 = 0, \quad R_2 = 1$
For the intermediate use cycle: $R_1 = 1, \quad R_2 = 1$
For the last use cycle: $R_1 = 1, \quad R_2 = 0$

For the first life cycle, the equation simplifies to:

$$EI_1 = EI_P + EI_C + EI_U \quad (5.2)$$

For the intermediate life cycle, the equation becomes:

$$EI_2 = EI_C + EI_U + EI_R \quad (5.3)$$

For the final life cycle, the equation is:

$$EI_3 = EI_C + EI_U + EI_{EoL} + EI_R \quad (5.4)$$

5.1.6. Considerations for Reuse in Consecutive Life Cycles

In assessing the environmental impact of a structural floor reused over three consecutive life cycles, it is essential to account for the reduction in structural capacity at each stage. As the floor is reused, its load-bearing capacity diminishes, necessitating additional materials or reinforcement to maintain its structural integrity. This section outlines the refined methodology for calculating the environmental impact across these life cycles, ensuring that each phase accurately reflects the cumulative effects of degradation and reuse.

Total Environmental Impact Over Three Life Cycles

The total environmental impact of the structural floor over the three life cycles is expressed as the sum of the impacts calculated for each individual life cycle:

$$\text{EI}_{\text{total}} = \text{EI}_1 + \text{EI}_2 + \text{EI}_3$$

The environmental impact of the first life cycle (EI_1) for reused slabs is calculated differently from the consecutive life cycles due to the allocation method discussed in Chapter 2.5. The allocation method must be incorporated into this methodology, leading to a more complex equation.

The production and construction impacts of the additional materials required for subsequent life cycles are added to the environmental impact of the second and third life cycles, as necessary. These additional materials are calculated using the methodology detailed in Section 2.3. Table 5.1 illustrates the final environmental impact allocation.

Table 5.1: Modified Environmental Impact Allocation Across Life Cycles

	First Life Cycle	Intermediate Life Cycle	Final Life Cycle
A1 – A3	$EI_{p,1}$	$EI_{p,2,\text{add}}$	$EI_{p,3,\text{add}}$
A4 – A5	$EI_{c,1}$	$EI_{c,1} + EI_{c,2,\text{add}}$	$(EI_{c,1} + EI_{c,2,\text{add}}) + EI_{c,3,\text{add}}$
B1 – B7	$EI_{u,1}$	$EI_{u,2}$	$EI_{u,3}$
C1 – C4	-	-	$EI_{\text{EoL},3}$
D	-	$EI_{R,1}$	$EI_{R,2}$

In each subsequent life cycle, additional environmental impacts are considered for any necessary intervention techniques. Specifically, $EI_{p,2,\text{add}}$ and $EI_{c,2,\text{add}}$ represent the environmental burdens associated with the production and construction of intervention techniques during the second life cycle. Similarly, for the third life cycle, $EI_{p,3,\text{add}}$ and $EI_{c,3,\text{add}}$ account for the impacts of further interventions. The necessity for these interventions and the cycles in which they are applied are determined based on structural assessments and design calculations, ensuring that the slab's integrity and functionality are preserved throughout its life cycle.

Concrete Strength Reduction

A key consideration when evaluating the long-term feasibility of slab reuse is the potential reduction in concrete compressive strength over time. In certain scenarios, significant strength loss may necessitate repairs or interventions, potentially increasing the overall environmental impact. However, this study determined (see Chapter 3.7.2) that, based on Goa's model [32], reductions in compressive strength do not require additional interventions, as described in Section 3.7.2. Consequently, typical degradation in concrete strength does not adversely affect the environmental performance of slabs, allowing for environmentally sustainable reuse without extra measures.

Corrosion of Steel Reinforcement

Corrosion of steel reinforcement is another critical factor affecting the reuse of concrete slabs, as it reduces the effective cross-sectional area of the steel and decreases the slab's bending moment capacity. Severe corrosion may necessitate interventions such as repair, strengthening, or partial replacement, potentially increasing the environmental impact. In this study, the effects of reinforcement corrosion over three life cycles were incorporated, and the structural implications are discussed in Section 3.7.3. The bending moment capacity calculations (M_{Rd}) are detailed in Appendix F. By accounting for corrosion effects, this research provides a more accurate evaluation of the environmental and structural viability of reusing floor systems.

5.1.7. Linear Building Economy vs. Circular Building Economy

In assessing environmental impacts, two distinct economic scenarios are considered: the Linear Economy (LE) and the Circular Economy (CE). In the Linear Economy scenario, material reuse is not assumed for consecutive life cycles, and the environmental impacts are calculated as if entirely new materials are used in each cycle. This approach reflects the full environmental burden of a traditional, single-use lifecycle model.

In contrast, the Circular Economy scenario incorporates the potential for reusing and extending the lifespan of materials, specifically prefabricated hollow core slabs and steel composite slabs. By allocating environmental benefits to reuse, this model highlights potential reductions in environmental impacts achievable through circular strategies. The comparison underscores the significant sustainability advantages of a circular economy approach, where material reuse is integrated into the life cycle analysis.

5.2. Application of the Framework to the Study

This section applies the developed life cycle assessment (LCA) framework to evaluate the environmental impacts of three floor systems: cast-in-situ concrete slabs, hollow-core slabs, and deep deck composite slabs, designed for a steel-framed building. Using GPR Materiaal, validated by the Nationale Milieu Database (NMD), this study analyzes the environmental performance of the slabs across three life cycles. By employing verified data and tools, this analysis aligns with international LCA standards and the Dutch Building Decree, ensuring reliable and practical insights for sustainable construction practices.

System Boundaries and Functional Unit

The analysis follows the system boundaries outlined in Chapter 5.1.1, covering production (Modules A1–A3), construction (A4–A5), and beyond-life (Module D). Impacts from the use stage (B1–B7) are excluded due to their minimal variation across slab types and dependence on building-specific factors [80, 81]. End-of-life impacts (C1–C4) are incorporated only for the final life cycle.

The functional unit is defined as one square meter of floor area, designed within a 5.4 x 2.5 m grid to achieve a bending moment unity check of 0.8 across three life cycles. This standardization ensures a fair comparison of material use, structural performance, and reuse potential for the floor systems.

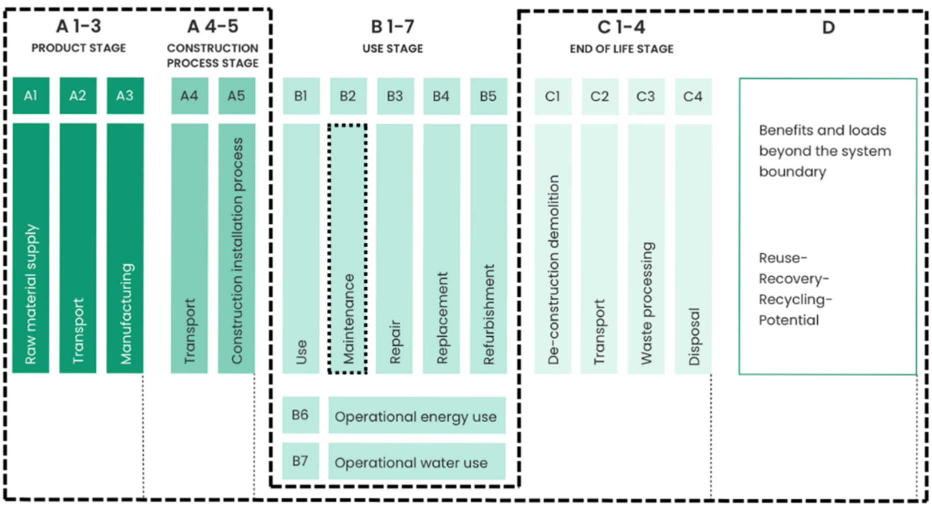


Figure 5.2: Modified System Boundary [72]

Environmental Assessment Setup

Selection of Environmental Impact Categories: Both Set A1 (11 mandatory categories) and Set A2 (expanded categories) were applied. Set A1 provides a baseline for compliance with current MPG regulations, while Set A2 offers forward-looking insights into the anticipated 2025 transition. This dual application ensures a comprehensive evaluation under both current and future standards.

Material Inventory: Material quantities, including concrete volume and reinforcement weight, were calculated for each slab design based on specifications detailed in Chapter 3. These values form the basis for precise environmental impact calculations.

Shadow Pricing Method: The Environmental Cost Indicator (ECI) was calculated for each slab using shadow pricing. This approach consolidates various environmental impacts into a single monetary metric, facilitating straightforward comparisons across slab designs and lifecycle stages.

GPR Materiaal: GPR Materiaal, one of the validated tools by NMD, was used to quantify the environmental impacts of the floor systems. Its integration with the NMD ensured accurate data for all materials, aligned with international standards (ISO 14040/14044) and Dutch regulations. This tool was chosen for its ability to provide detailed impact results across multiple categories, enabling robust and consistent assessments.

Data Categories

The environmental data for the materials used in this study were classified based on the Nationale Milieu Database (NMD) categories, which reflect different levels of data quality and reliability:

- **Category 1:** High-quality, manufacturer-specific data verified by the NMD. Both Slab 1 (cast-in-situ concrete C20/25) and Slab 2 (hollow-core slab by VBI) utilize this category, ensuring precise and representative assessments.
- **Category 2:** Industry-average data independently verified to reflect the Dutch market. Although not used in this study, it provides a reasonable fallback when Category 1 data is unavailable.
- **Category 3:** Generic, unverified data used as a last resort. Slab 3 (deep deck composite slab with a plate depth of 210 mm) relies on Category 3 data, with a 30% markup applied to account for potential underestimations.

Allocation Method and Life Cycle Interventions

The cut-off approach was employed to allocate environmental impacts across the three life cycles. Impacts from material extraction and production (A1–A3) were assigned to the first life cycle, while reuse-related impacts, such as those arising from structural interventions, were attributed to the subsequent life cycles.

For the hollow-core slab (Slab 2), an intervention was required due to degradation factors. Steel plate bonding was implemented to address corrosion-related deterioration in the second and third life cycles, as detailed in Section 3.7.5. These interventions were incorporated into the environmental impact calculations to provide a realistic assessment of the trade-offs involved in reuse strategies. Detailed calculations for the structural interventions are presented in Appendix F.

5.3. Environmental Impact Results

This section presents the environmental impact results for the three slab designs evaluated in this study. The impacts are calculated based on the previously defined environmental impact categories (Set A1 and Set A2) and life cycle stages. The results are expressed per functional unit, defined as one square meter of slab. The total impacts for each slab are calculated by summing the contributions from the relevant life cycle stages as outlined in the methodology.

5.3.1. Results per Environmental Impact Category

The environmental impacts for each slab are presented separately to provide a clear understanding of their individual performance across the different impact categories.

Slab 1: Cast In-Situ Concrete Slab

Tables 5.2 and Table H.2 in Appendix H present the environmental impact results for Slab 1 based on Set A1 and Set A2 categories, respectively. The impacts are calculated for the various life cycle stages and are presented as total values.

In Table 5.2, the total environmental impacts for Slab 1 are calculated by summing the contributions from production (A1–A3), construction (A4–A5), and end-of-life (C1–C4) stages, and accounting for credits from module D. Key observations include that the total Climate Change (GWP) impact is 38.1 kg CO_2 eq, with the production stage contributing the most. The Human Toxicity Potential (HTP) shows a total impact of 14.1 kg 1,4-DCB eq, indicating significant potential effects on human health. The Environmental Cost Indicator (ECI), representing the weighted sum of the impacts, amounts to €4.34 for Slab 1.

Table 5.2: Environmental Impact Results for Slab 1 (Set A1)

Set A1	A1 - A3	A4 - A5	C1 - C4	D	Total
Depletion of abiotic resources minerals and metals	1.39E-4	6.78E-5	7.86E-5	-6.82E-5	2.17E-4
Depletion of abiotic resources fossil fuels	1.72E-1	2.98E-2	4.39E-2	-1.88E-2	2.27E-1
Climate change	3.07E1	4.15E0	6.30E0	-3.00E0	3.81E1
Ozone layer depletion	1.80E-6	6.74E-7	1.05E-6	-1.71E-7	3.35E-6
Photochemical Oxidation	2.11E-2	3.18E-3	5.12E-3	-5.02E-3	2.44E-2
Acidification	1.11E-1	2.13E-2	3.89E-2	-1.33E-2	1.58E-1
Eutrophication	1.76E-2	4.27E-3	8.38E-3	-1.84E-3	2.84E-2
Human Toxicity	1.14E1	1.78E0	2.61E0	-1.66E0	1.41E1
Freshwater Aquatic Ecotoxicity	3.54E-1	4.79E-2	5.32E-2	1.44E-2	4.69E-1
Marine Aquatic Ecotoxicity	8.37E2	1.53E2	1.96E2	-1.09E1	1.18E3
Terrestrial Ecotoxicity	8.10E-1	3.50E-2	8.18E-3	1.34E-1	9.87E-1

In Table H.2, the expanded assessment includes additional impact categories. Notable results are the total Global Warming Potential (GWP-total) of 47.5 kg CO_2 eq, and the Abiotic Depletion Potential for Fossil Resources (ADP-fossil) amounting to 492 MJ, indicating significant fossil fuel consumption. The detailed results for Set A2 are provided in Appendix H.

Slab 2: Hollow Core Slab

Table 5.3 presents the environmental impact results for Slab 2 based on Set A1 categories. The impacts are calculated for the various life cycle stages and are presented as total values.

In Table 5.3, the total environmental impacts for Slab 2 are calculated by summing the contributions from production (A1–A3), construction (A4–A5), and end-of-life (C1–C4) stages, and accounting for credits from module D. Key results include a total Climate Change (GWP) impact of 29.2 kg CO_2 eq, and a Human Toxicity Potential (HTP) of 6.18 kg 1,4-DCB eq. The Environmental Cost Indicator (ECI) amounts to €2.61 for Slab 2.

An expanded assessment using Set A2 categories provides additional data. The total Global Warming Potential (GWP-total) is 31.2 kg CO_2 eq, and the Abiotic Depletion Potential for Fossil Resources (ADP-fossil) is 262 MJ. The ECI for Set A2 is €5.26 for Slab 2. Detailed results for Set A2 are provided in Appendix H.

Table 5.3: Environmental Impact Results for Slab 2 (Set A1)

Set A2	A1 - A3	A4 - A5	C1 - C4	D	Total
Depletion of abiotic resources minerals and metals	1.05E-4	3.33E-5	3.34E-5	-3.47E-5	1.37E-4
Depletion of abiotic resources fossil fuels	1.19E-1	1.73E-2	1.26E-2	-1.35E-2	1.36E-1
Climate change	2.71E1	2.55E0	1.74E0	-2.14E0	2.92E1
Ozone layer depletion	1.22E-6	3.91E-7	2.87E-7	-1.16E-7	1.78E-6
Photochemical Oxidation	1.10E-2	1.55E-3	1.14E-3	-3.78E-3	9.87E-3
Acidification	6.85E-2	8.00E-3	8.74E-3	-9.01E-3	7.63E-2
Eutrophication	1.44E-2	1.46E-3	1.81E-3	-1.22E-3	1.65E-2
Human Toxicity	5.67E0	1.02E0	7.28E-1	-1.23E0	6.18E0
Freshwater Aquatic Ecotoxicity	2.74E-1	2.71E-2	1.81E-2	8.16E-3	3.27E-1
Marine Aquatic Ecotoxicity	4.55E2	9.99E1	6.72E1	-7.70E0	6.14E2
Terrestrial Ecotoxicity	3.67E-1	1.01E-2	3.01E-3	8.65E-2	4.67E-1

Slab 3: Deep Deck Composite Slab

Table 5.4 presents the environmental impact results for Slab 3 based on Set A1 categories. The total impacts are calculated for the life cycle stages and are expressed per functional unit.

Key results for Slab 3 include a total Climate Change (GWP) impact of 26.7 kg CO_2 eq. The Human Toxicity Potential (HTP) is 3.34 kg 1,4-DCB eq, and the Environmental Cost Indicator (ECI) amounts to €2.27.

An expanded assessment using Set A2 categories provides additional data. The total Global Warming Potential (GWP-total) is 40.3 kg CO_2 eq, and the Abiotic Depletion Potential for Fossil Resources (ADP-fossil) is 326 MJ. The ECI for Set A2 is €7.45 for Slab 3. Detailed results for Set A2 are provided in Appendix H.

Table 5.4: Environmental Impact Results for Slab 3 (Set A1)

Set A1 (Slab 3)	A1 - A3	A4 - A5	C1 - C4	D	Total
Depletion of abiotic resources minerals and metals	4.84E-5	3.50E-6	1.52E-6	-1.90E-5	3.45E-5
Depletion of abiotic resources fossil fuels	2.02E-1	9.17E-3	3.90E-3	-7.25E-2	1.42E-1
Climate change	3.95E1	1.24E0	5.21E-1	-1.46E1	2.67E1
Ozone layer depletion	8.14E-7	2.26E-7	1.42E-7	-2.69E-9	1.18E-6
Photochemical Oxidation	1.83E-2	7.38E-4	4.23E-4	-7.51E-3	1.19E-2
Acidification	1.20E-1	5.37E-3	2.73E-3	-2.73E-2	1.01E-1
Eutrophication	1.32E-2	1.07E-3	6.20E-4	-1.57E-3	1.33E-2
Human Toxicity	2.64E0	4.97E-1	2.40E-1	-3.77E-2	3.34E0
Freshwater Aquatic Ecotoxicity	1.02E-1	1.46E-2	6.51E-3	-1.80E-2	1.05E-1
Marine Aquatic Ecotoxicity	5.19E2	5.23E1	4.02E1	6.85E-1	6.12E2
Terrestrial Ecotoxicity	5.29E-2	2.48E-3	1.98E-3	4.29E-3	6.16E-2

5.3.2. Environmental Cost Indicator (ECI) Results

The Environmental Cost Indicator (ECI) consolidates the environmental impacts across various categories into a single monetary value, facilitating a straightforward comparison between different slab designs. Tables 5.5 and 5.6 present the ECI values for each slab per life cycle stage, based on Set A1 and Set A2 impact categories, respectively.

Table 5.5: Environmental Cost Indicator for Set A1

ECI (Set A1)	A1 - A3	A4 - A5	C1 - C4	D	Total
Slab 1	€3.38	€0.52	€0.82	€-0.37	€4.34
Slab 2	€2.39	€0.28	€0.22	€-0.27	€2.61
Slab 3	€2.94	€0.15	€0.07	€-0.88	€2.27

Table 5.5 shows that for Set A1 impact categories, Slab 1 has the highest total ECI of €4.34, with the production stage (A1–A3) contributing the most significant portion. Slab 2 has a total ECI of €2.61, and Slab 3 has the lowest total ECI at €2.27.

Table 5.6: Environmental Cost Indicator for Set A2

ECI (Set A2)	A1 - A3	A4 - A5	C1 - C4	D	Total
Slab 1	€7.29	€1.09	€1.74	€-0.59	€9.53
Slab 2	€4.69	€0.56	€0.40	€-0.40	€5.26
Slab 3	€6.72	€0.61	€0.41	€-0.30	€7.45

Table 5.6 presents the ECI values based on Set A2 impact categories, which include additional environmental aspects and a different weighing method. The total ECI values are higher in this set due to the expanded scope of impacts considered. Specifically, Slab 1 has a total ECI of €9.53, Slab 2 has €5.26, and Slab 3 has €7.45.

These ECI results provide a clear comparative overview of the environmental costs associated with each slab design across different life cycle stages. The production stage (A1–A3) remains the most significant contributor to the total ECI for all slabs, highlighting the importance of material selection and manufacturing processes.

5.4. Summary

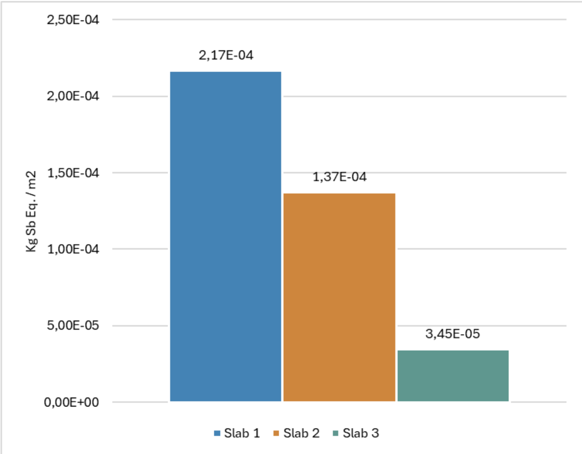
This chapter detailed the environmental impact assessment of three slab designs: Cast In-Situ Concrete Slab (Slab 1), Hollow Core Slab (Slab 2), and Deep Deck Composite Slab (Slab 3). The assessment utilized two sets of environmental impact categories, Set A1 and Set A2, to evaluate each slab's performance across various environmental dimensions.

The Environmental Cost Indicator (ECI) was employed to quantify the overall environmental costs associated with each slab design. Based on Set A1 categories, Slab 1 recorded the highest ECI of €4.34, followed by Slab 2 at €2.61 and Slab 3 at €2.27. When expanding the assessment to Set A2 categories, the ECI values increased for all slabs, with Slab 1 at €9.53, Slab 2 at €5.26, and Slab 3 at €7.45.

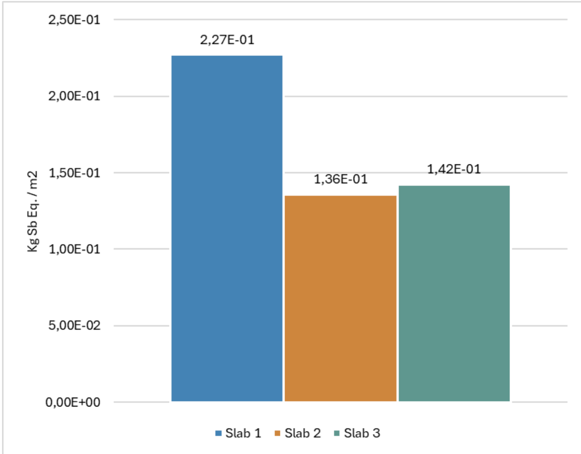
In addition to the ECI, key environmental impact categories such as Global Warming Potential (GWP), Abiotic Depletion Potential (ADP), Acidification Potential (AP), Eutrophication Potential (EP), and Human Toxicity Potential (HTP) were analyzed. Across both sets of impact categories, Slab 1 consistently exhibited higher impacts in GWP, ADP, AP, EP, and HTP compared to Slab 2 and Slab 3. Slab 2 and Slab 3 demonstrated lower environmental impacts, with Slab 2 often showing the most favorable performance among the three.

The comparative results highlight the relative environmental efficiencies of the slab designs, establishing a foundation for the detailed analysis and discussion that will follow in the next chapter. These findings underscore the importance of selecting slab designs that minimize environmental costs and impacts, contributing to more sustainable construction practices.

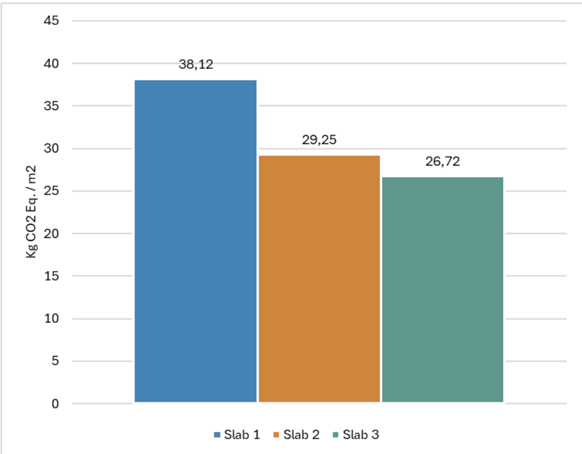
The detailed environmental impact results for each slab per category is shown in Figure 5.3.



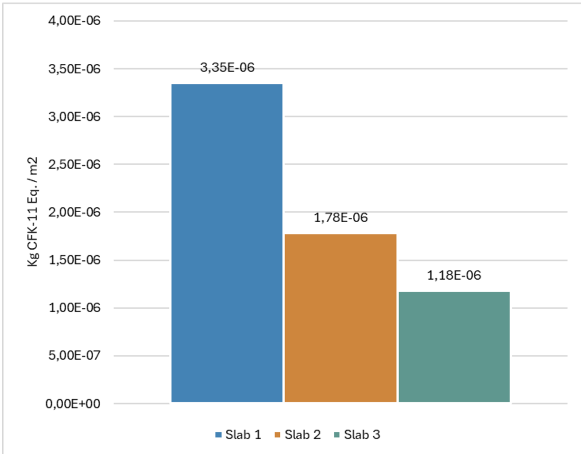
(a) Abiotic Depletion Potential Minerals and Metals



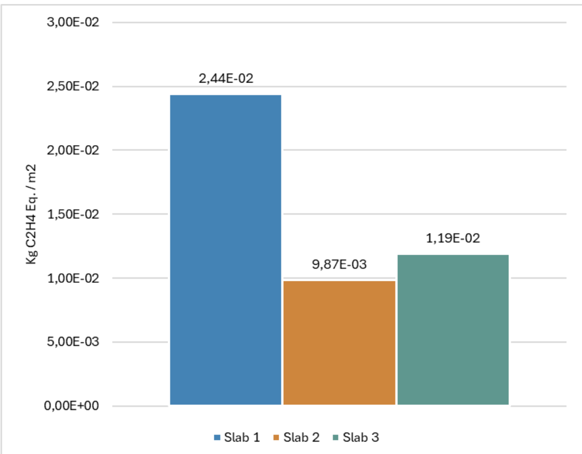
(b) Abiotic Depletion Potential Fossil Fuels



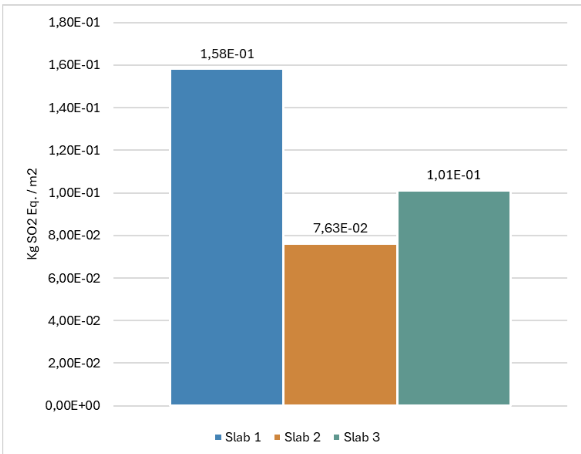
(c) Global Warming Potential



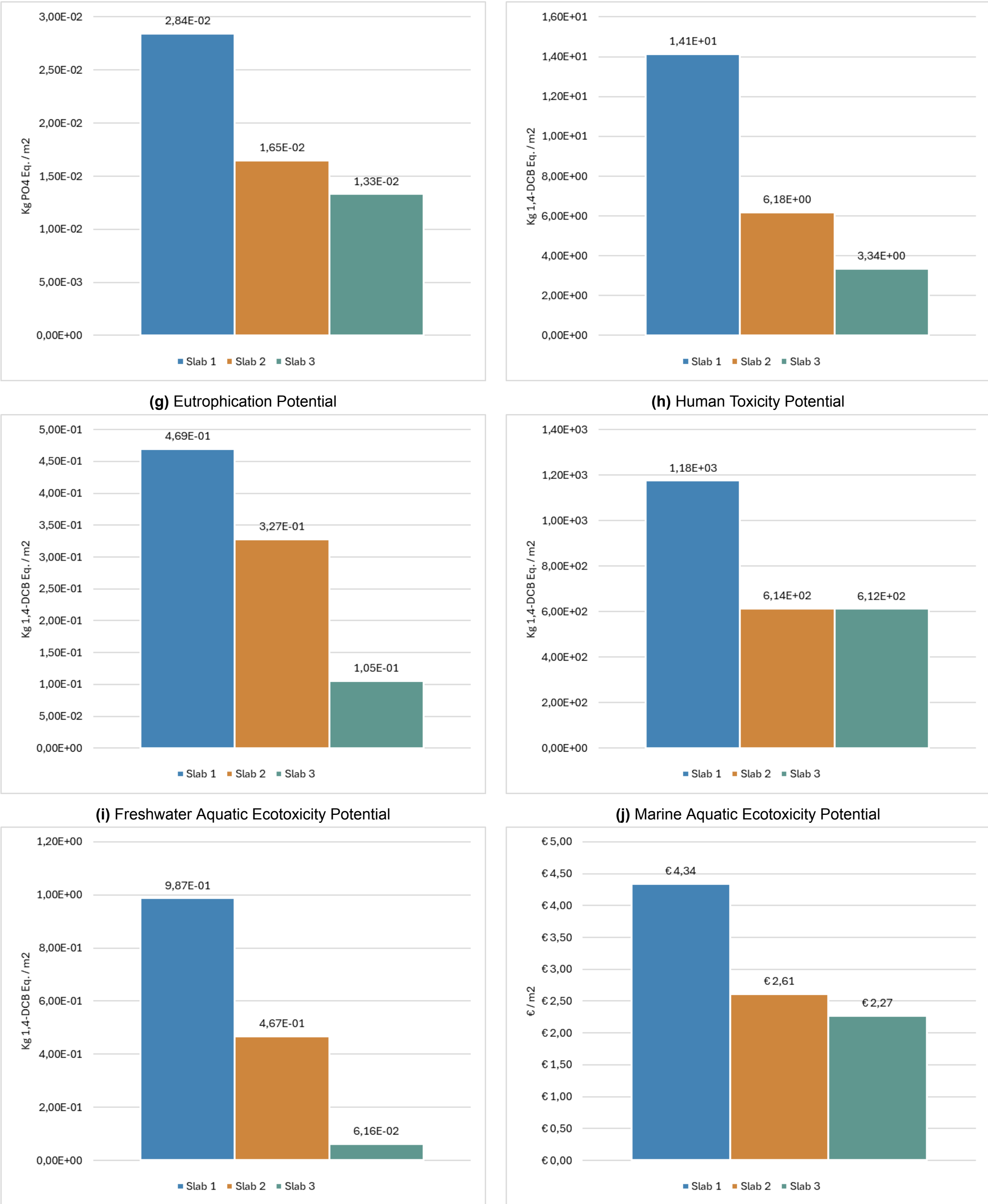
(d) Ozone Layer Depletion Potential



(e) Photochemical Oxidation Potential



(f) Acidification Potential



(g) Eutrophication Potential

(h) Human Toxicity Potential

(i) Freshwater Aquatic Ecotoxicity Potential

(j) Marine Aquatic Ecotoxicity Potential

(k) Terrestrial Ecotoxicity Potential

(l) Environmental Cost Indicator

Figure 5.3: Environmental Impact Results for Each Slab per Category

6
Results & Analysis

This chapter analyzes the environmental impact results from Chapter 5. It compares the results across different life cycles of the floor systems, discussing how each construction method affects environmental sustainability. This detailed analysis will help understand the long-term effects of each system.

6.1. Analysis of Environmental Impact Results

This section evaluates the environmental impacts of floor systems across various life cycles. It begins with a comprehensive assessment of a single life cycle, followed by an extension to multi-life cycle scenarios. In multi-life cycle analyses, an allocation method is applied to distribute the environmental impacts appropriately over the life cycles. This distinction is important, as it differentiates the first life cycle in multi-cycle scenarios from the single life cycle analysis, which consolidates all stages into one cycle. This approach highlights how environmental impacts evolve when floor systems are reused across multiple life cycles.

6.1.1. Single Life Cycle Analysis

The results for a single life cycle using Set A1 illustrates a nuanced picture across different environmental impact categories. Slab 1 (Cast In-Situ Concrete Slab), with its traditional construction approach, generally exhibits higher environmental impacts. This is evident in its usage of substantial amounts of concrete and the need for on-site formwork, which increases resource use and associated emissions.

Slab 2 (Hollow Core Slab), although prefabricated and expected to offer environmental benefits due to reduced on-site work, does show mixed results. Notably, it has the highest impact in the Human Toxicity category, which suggests that while prefabrication reduces some impacts, the materials or processes involved in creating the hollow core slabs may contribute significantly to toxicity potentials. However, it performs better than Slab 1 in several other categories, such as Marine Aquatic Ecotoxicity and Terrestrial Ecotoxicity, highlighting the benefits of its manufacturing process.

Slab 3 (Deep Deck Composite Slab), which combines a steel deck with a cast-in-situ concrete topping, shows the lowest values in most categories, particularly Terrestrial Ecotoxicity and Freshwater Aquatic Ecotoxicity. The reduced concrete usage through composite action helps lower its overall environmental footprint. However, this slab does not always outperform Slab 2 due to the environmental load associated with steel production, evident in its impact scores for Depletion of abiotic resources (fossil fuels) and certain toxicity measures.

The comparison reveals that while Slab 2 often shows favorable outcomes, such as lower impacts in Photochemical Oxidation and Acidification, it does not universally outperform the others, especially in Human Toxicity where it ranks the highest (worst). Slab 3 frequently outperforms both Slab 1 and Slab 2 in categories critical to ecosystem and human health impacts due to its innovative construction technique, though its dependence on steel moderates these advantages.

This analysis highlights that while prefabrication and innovative material use can significantly reduce environmental impacts, the choice of materials and manufacturing processes are crucial in determining the overall environmental performance of construction methods. Detailed values for each environmental impact category of Set A1 can be seen in Table 6.1, and for Set A2 in Table H.5 in Appendix H.

Table 6.1: Environmental Impact Results for Different Slabs for 1 Life Cycle

SET A1	**Slab 1**	**Slab 2**	**Slab 3**	**Units**
ADP-minerals&metals	2.17E-04	1.37E-04	3.45E-05	Kg Sb Eq. / m2
ADP-fossil	2.27E-01	1.36E-01	1.42E-01	Kg Sb Eq. / m2
GWP-total	3.81E+01	2.92E+01	2.67E+01	Kg CO2 Eq. / m2
ODP	3.35E-06	1.78E-06	1.18E-06	Kg CFC-11 Eq. / m2
POCP	2.44E-02	9.87E-03	1.19E-02	Kg C2H4 Eq. / m2
AP	1.58E-01	7.63E-02	1.01E-01	Kg SO2 Eq. / m2
EP	2.84E-02	1.65E-02	1.33E-02	Kg PO4 Eq. / m2
HTP	1.41E+01	6.18E+00	3.34E+00	Kg 1,4-DCB Eq. / m2
FAETP	4.69E-01	3.27E-01	1.05E-01	Kg 1,4-DCB Eq. / m2
MAETP	1.18E+03	6.14E+02	6.12E+02	Kg 1,4-DCB Eq. / m2
TETP	9.87E-01	4.67E-01	6.16E-02	Kg 1,4-DCB Eq. / m2
ECI	**€ 4.34**	**€ 2.61**	**€ 2.27**	€ / m2

6.1.2. Multi-Life Cycle Analysis

The environmental impact results for two life cycles (Table 6.2) highlight the benefits of a circular economy approach, particularly for Slab 2 and Slab 3, which incorporate material reuse. In contrast, Slab 1, following a linear economy model, incurs consistent environmental impacts across both life cycles due to the lack of reuse.

While Slab 2 demonstrates lower overall impacts than Slab 1, the required strengthening to address corrosion adds environmental burdens, especially in categories such as Global Warming Potential (GWP) and Depletion of Abiotic Resources (fossil fuels). Despite this, both Slab 2 and Slab 3 achieve significantly lower overall impacts over two life cycles compared to Slab 1, underscoring the sustainability benefits of adopting circular economy principles.

For instance, the Global Warming Potential (GWP) of Slab 2 decreases by 58.4% compared to Slab 1, while the Depletion of Abiotic Resources (fossil fuels) is reduced by 66.5%. Slab 3, despite not requiring strengthening, exhibits a 63.3% reduction in GWP compared to Slab 1, and a 66.6% reduction in Depletion of Abiotic Resources. These reductions emphasize the clear sustainability benefits of the circular building economy, with Slab 3 performing the best overall.

Table 6.2: Environmental Impact Results Across Slabs over Two Life Cycles (Set A1)

Category	Slab 1 (LE)	Slab 2 (CE)	Slab 3 (CE)	Units
ADP-minerals&metals	4.34E-04	1.72E-04	3.80E-05	Kg Sb Eq. / m2
ADP-fossil	4.54E-01	1.53E-01	1.52E-01	Kg Sb Eq. / m2
GWP-total	7.62E+01	3.17E+01	2.80E+01	Kg CO2 Eq. / m2
ODP	6.71E-06	2.18E-06	1.41E-06	Kg CFC-11 Eq. / m2
POCP	4.88E-02	1.07E-02	1.26E-02	Kg C2H4 Eq. / m2
AP	3.16E-01	8.42E-02	1.06E-01	Kg SO2 Eq. / m2
EP	5.69E-02	1.80E-02	1.44E-02	Kg PO4 Eq. / m2
HTP	2.83E+01	7.10E+00	3.84E+00	Kg 1,4-DCB Eq. / m2
FAETP	9.39E-01	3.62E-01	1.20E-01	Kg 1,4-DCB Eq. / m2
MAETP	2.35E+03	7.29E+02	6.64E+02	Kg 1,4-DCB Eq. / m2
TETP	1.97E+00	5.10E-01	6.41E-02	Kg 1,4-DCB Eq. / m2
ECI	**8.69**	**2.88**	**2.42**	€ / m2

When examining the three life cycle analysis (Table 6.3), the circular economy approach's advantages become even more pronounced. By including an intermediate life cycle that omits production and end-of-life stages, substantial reductions in environmental impacts are achieved. For Slab 3, which does not require strengthening, the impacts are significantly lower across all categories. The environmental impacts of Slab 3 decrease by 87.2% in GWP and 87.0% in ADP-fossil when compared to Slab 1. These reductions are further strengthened by the elimination of production and end-of-life costs during intermediate cycles, emphasizing the sustainability benefits of material reuse.

Table 6.3: Environmental Impact Results for Slabs over Three Life Cycles (Set A1)

Category	Slab 1 (LE)	Slab 2 (CE)	Slab 3 (CE)	Units
ADP-minerals&metals	6.50E-04	1.72E-04	2.25E-05	Kg Sb Eq. / m2
ADP-fossil	6.81E-01	1.55E-01	8.83E-02	Kg Sb Eq. / m2
GWP-total	1.14E+02	3.18E+01	1.46E+01	Kg CO2 Eq. / m2
ODP	1.01E-05	2.45E-06	1.63E-06	Kg CFC-11 Eq. / m2
POCP	7.32E-02	7.79E-03	5.88E-03	Kg C2H4 Eq. / m2
AP	4.75E-01	8.24E-02	8.45E-02	Kg SO2 Eq. / m2
EP	8.53E-02	1.82E-02	1.39E-02	Kg PO4 Eq. / m2
HTP	4.24E+01	6.71E+00	4.30E+00	Kg 1,4-DCB Eq. / m2
FAETP	1.41E+00	4.04E-01	1.17E-01	Kg 1,4-DCB Eq. / m2
MAETP	3.53E+03	8.31E+02	7.17E+02	Kg 1,4-DCB Eq. / m2
TETP	2.96E+00	6.38E-01	7.09E-02	Kg 1,4-DCB Eq. / m2
ECI	**13.03**	**2.86**	**1.68**	€ / m2

Slab 2, although requiring strengthening to address durability concerns, still performs better than Slab 1 over three life cycles. For instance, Slab 2 achieves a 72.1% reduction in GWP and a 77.2% reduction in ADP-fossil compared to Slab 1. However, the strengthening interventions introduce additional environmental burdens, particularly in Human Toxicity and Freshwater Aquatic Ecotoxicity, where Slab 2 records 6.71 Kg 1,4-DCB Eq./m² and 0.404 Kg 1,4-DCB Eq./m², respectively.

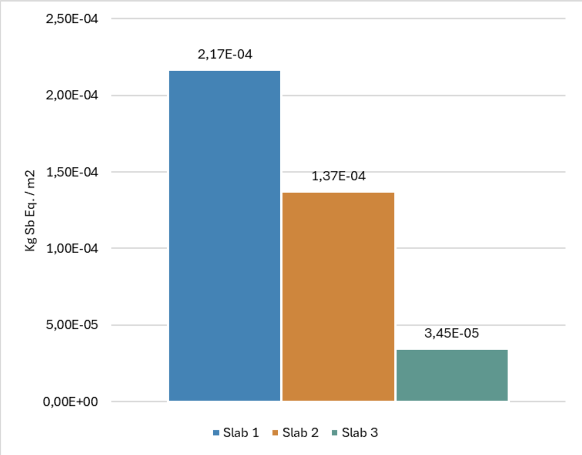
A comparison between Slab 2 and Slab 3 highlights notable differences. While Slab 2 performs well in categories such as POCP and AP due to its prefabricated nature and reduced emissions during construction, it falls short compared to Slab 3 in most categories. Slab 3 outperforms Slab 2 in GWP, ECI, and TETP, achieving reductions of 54.1%, 41.3%, and 88.9%, respectively, compared to Slab 2.

This superior performance can be attributed to the optimized composite design of Slab 3, specifically the contribution of the steel decking and the concrete topping. The steel decking enhances tensile capacity and reduces the need for reinforcement, while the concrete topping provides compressive strength, enabling efficient load distribution. By combining these elements, Slab 3 minimizes material use while maintaining structural efficiency, resulting in lower environmental impacts across multiple categories.

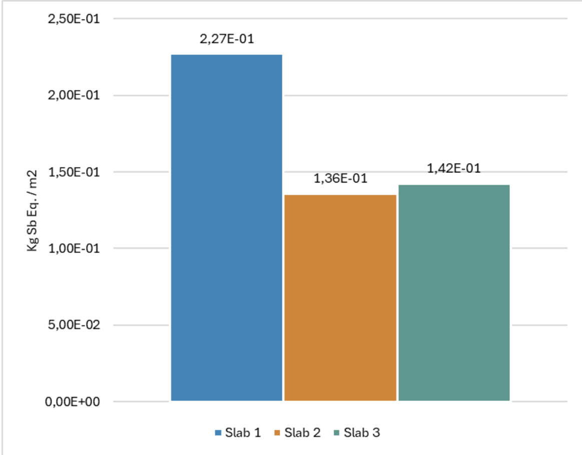
In conclusion, the circular economy approach adopted by Slab 2 and Slab 3 demonstrates significant advantages over the linear economy model of Slab 1. Over three life cycles, Slab 3 emerges as the most sustainable floor system, achieving an 87.2% reduction in GWP and an 87.1% reduction in ECI compared to Slab 1. Slab 2 also shows substantial improvements over Slab 1 but remains less efficient than Slab 3 due to the environmental costs of strengthening. These results emphasize the value of designing for material reuse and minimizing interventions to achieve maximum sustainability benefits.

6.1.3. Overview of Results

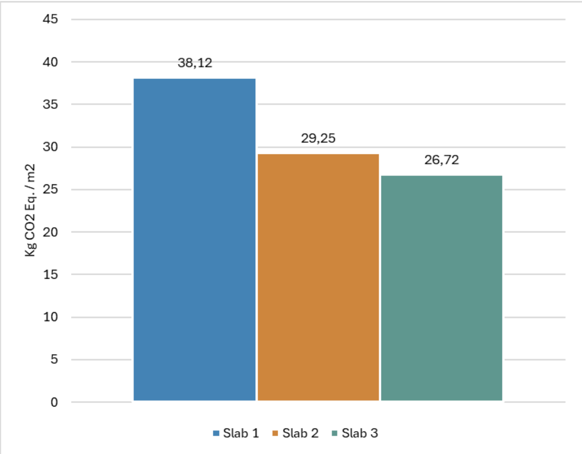
In this section, an overview of all the Set A1 data is provided to maintain coherence throughout the report. The results include the environmental impact results for each slab per category for a single life cycle, the environmental impact results for each slab per category for two life cycles, and the environmental impact results for each slab per category for three life cycles.



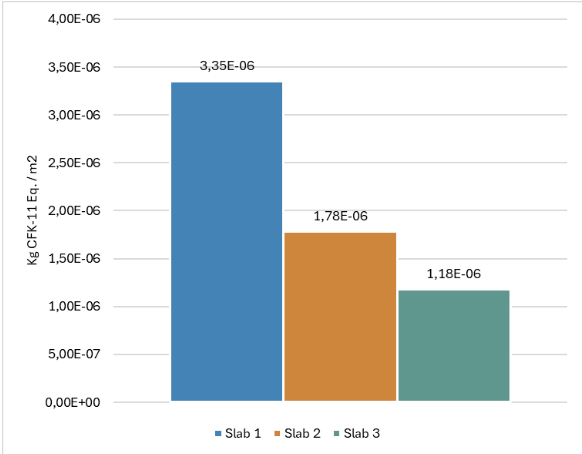
(a) Abiotic Depletion Potential Minerals and Metals



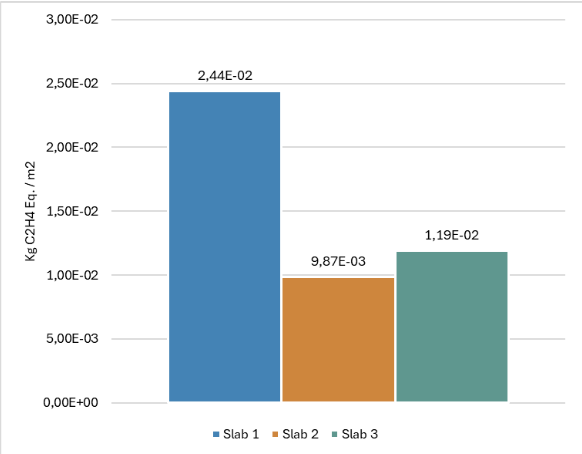
(b) Abiotic Depletion Potential Fossil Fuels



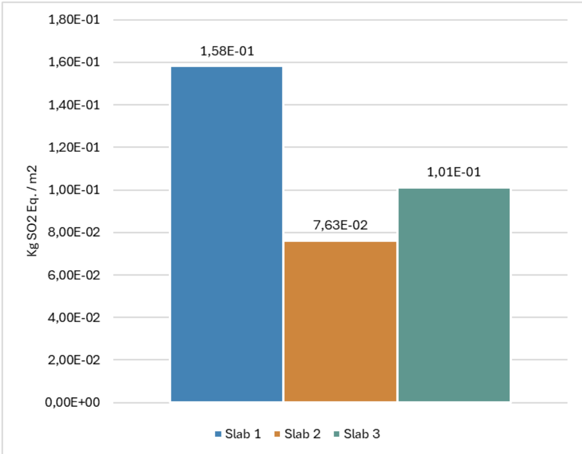
(c) Global Warming Potential



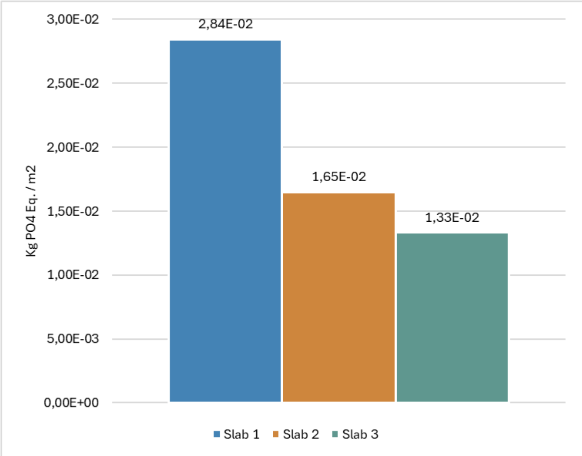
(d) Ozone Layer Depletion Potential



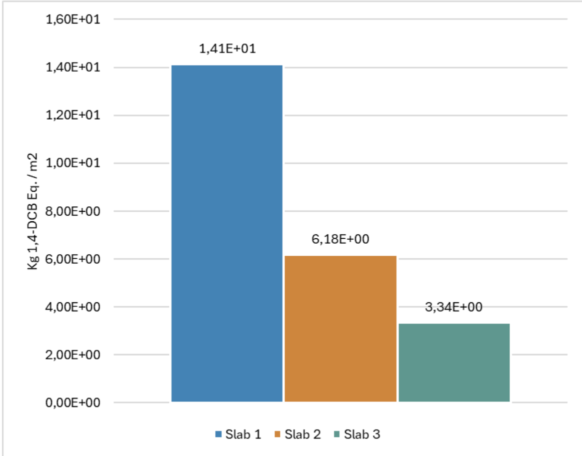
(e) Photochemical Oxidation Potential



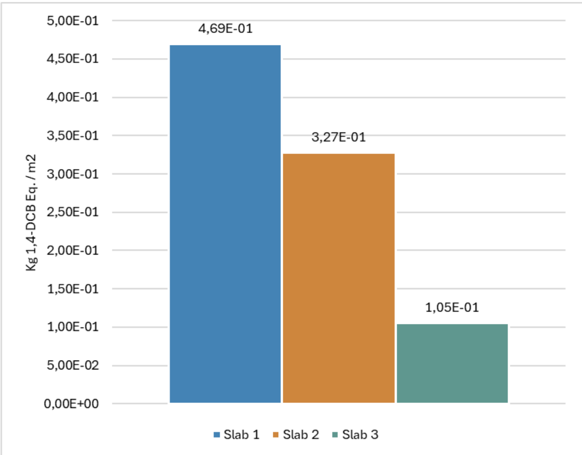
(f) Acidification Potential



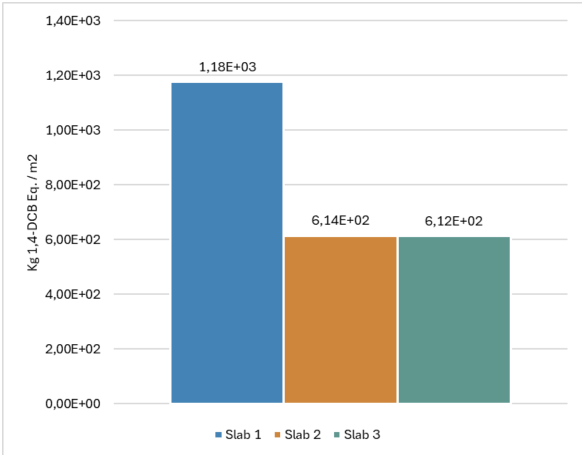
(g) Eutrophication Potential



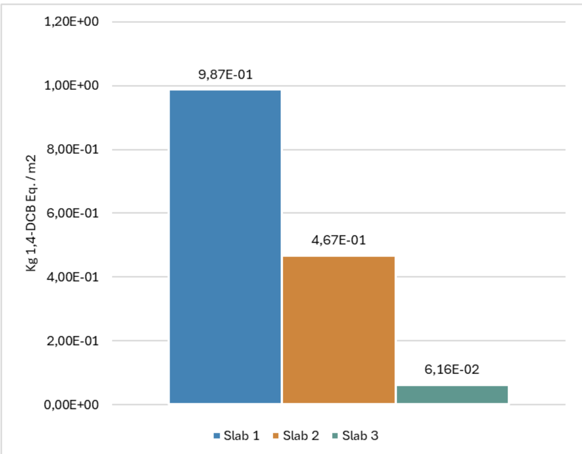
(h) Human Toxicity Potential



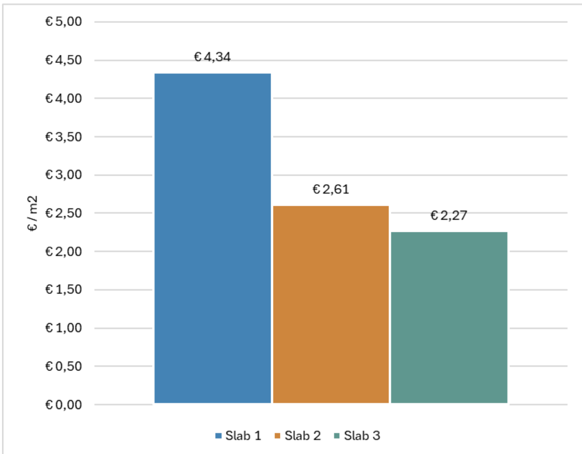
(i) Freshwater Aquatic Ecotoxicity Potential



(j) Marine Aquatic Ecotoxicity Potential

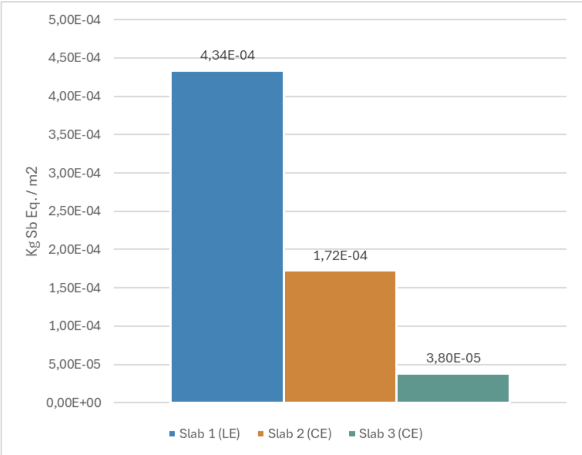


(k) Terrestrial Ecotoxicity Potential

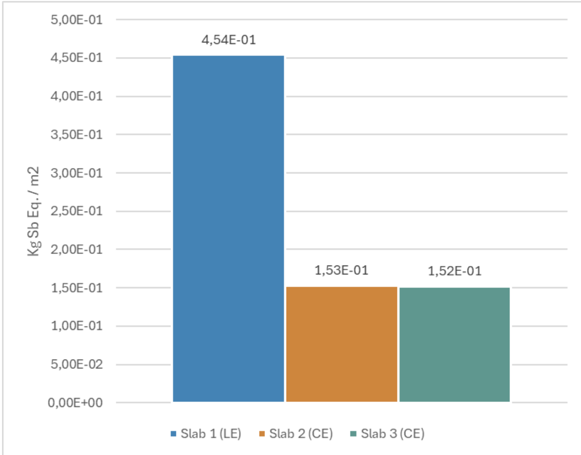


(l) Environmental Cost Indicator

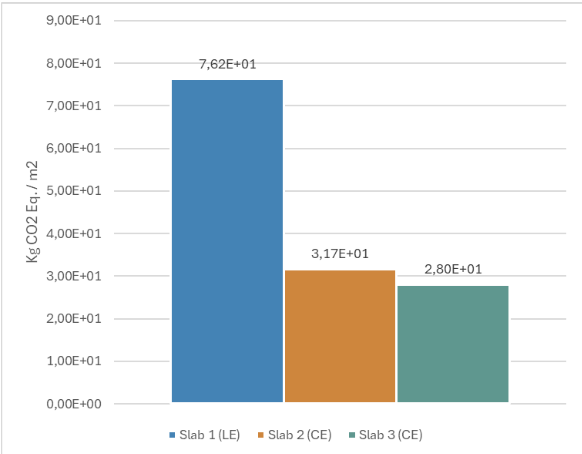
Figure 6.1: Environmental Impact over a Single Life Cycle for Set A1



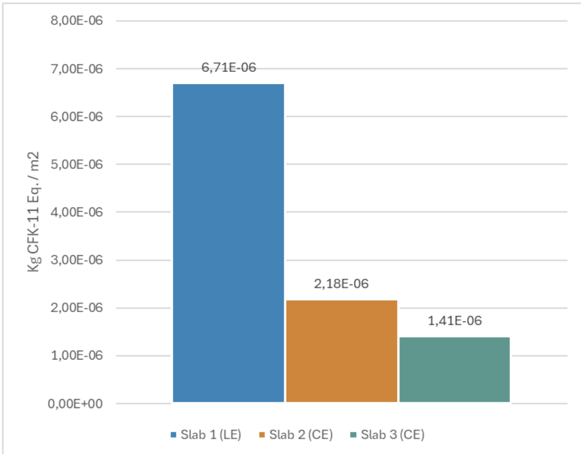
(a) Abiotic Depletion Potential Minerals and Metals



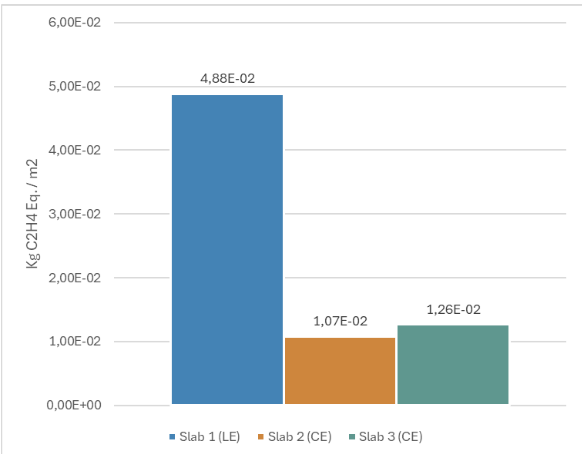
(b) Abiotic Depletion Potential Fossil Fuels



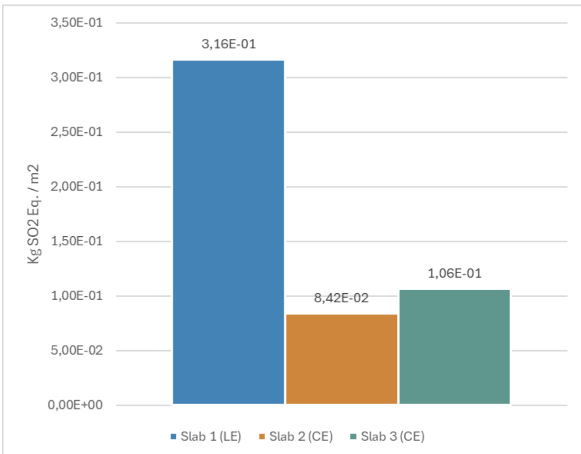
(c) Global Warming Potential



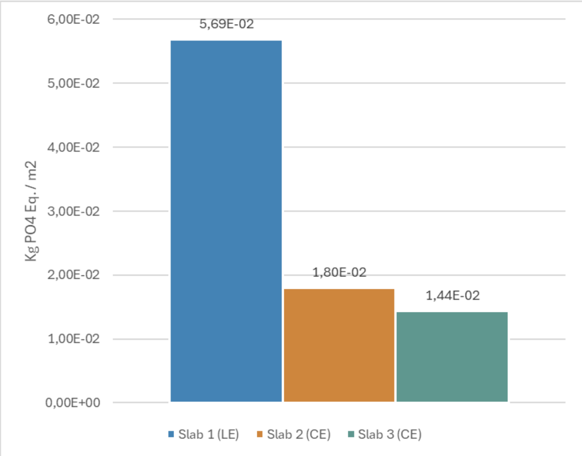
(d) Ozone Layer Depletion Potential



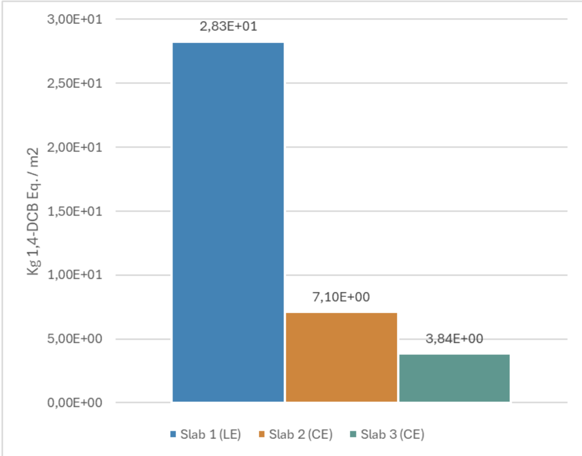
(e) Photochemical Oxidation Potential



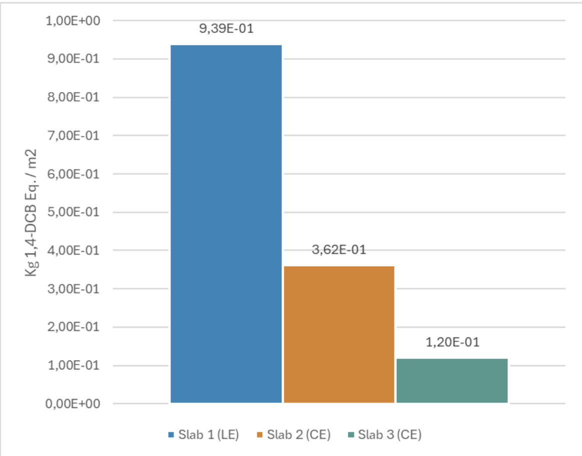
(f) Acidification Potential



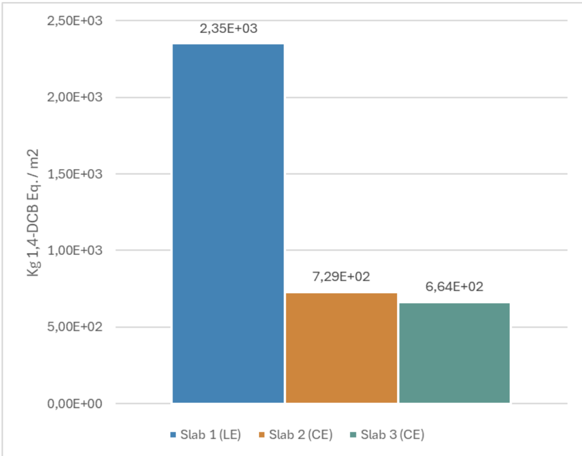
(g) Eutrophication Potential



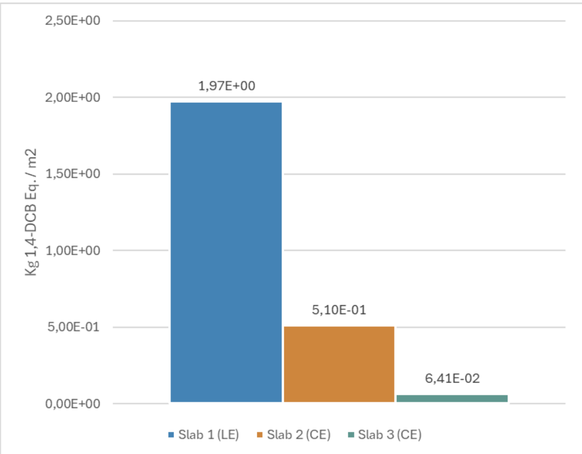
(h) Human Toxicity Potential



(i) Freshwater Aquatic Ecotoxicity Potential



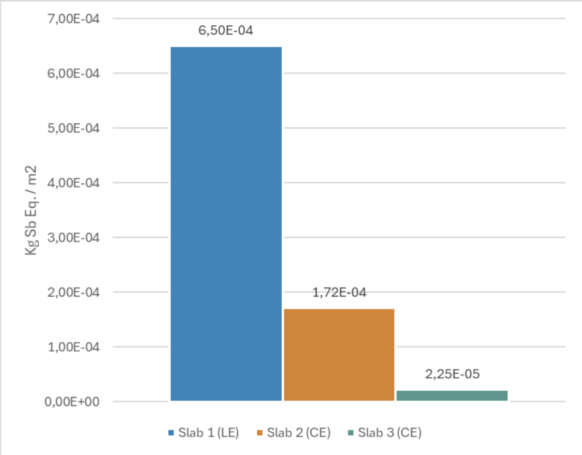
(j) Marine Aquatic Ecotoxicity Potential



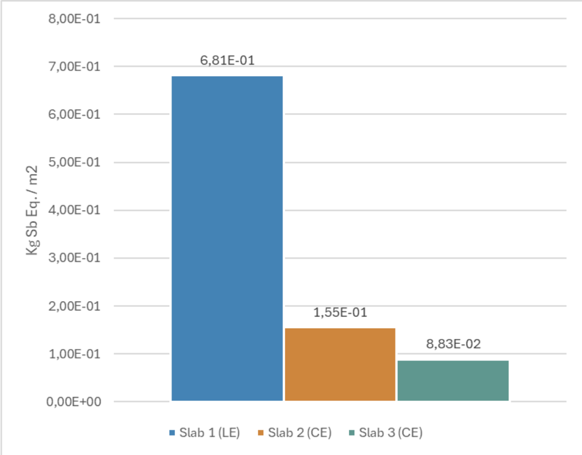
(k) Terrestrial Ecotoxicity Potential

(l) Environmental Cost Indicator

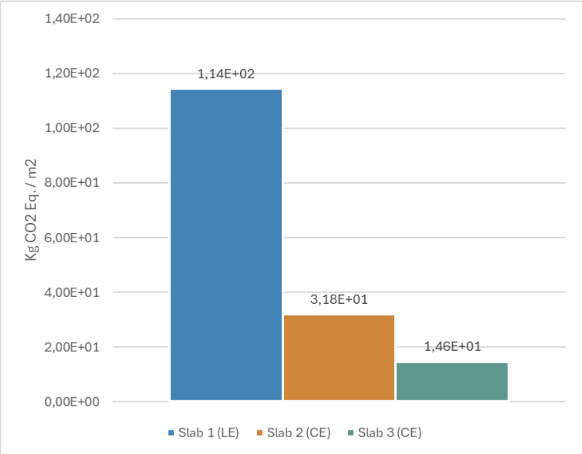
Figure 6.2: Environmental Impact over Two Life Cycles for Set A1



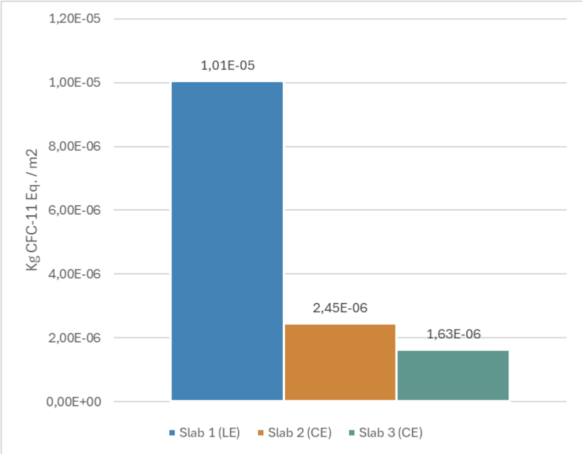
(a) Abiotic Depletion Potential Minerals and Metals



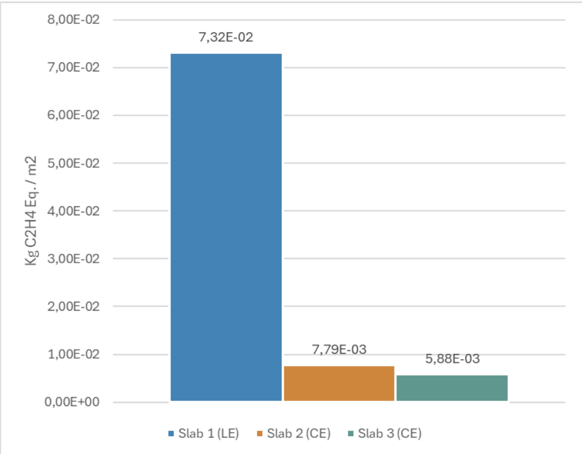
(b) Abiotic Depletion Potential Fossil Fuels



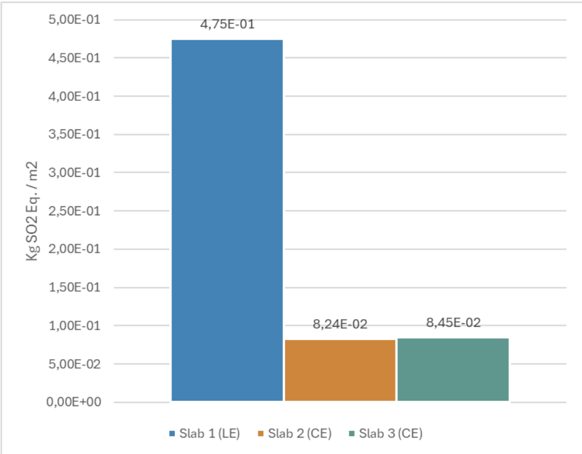
(c) Global Warming Potential



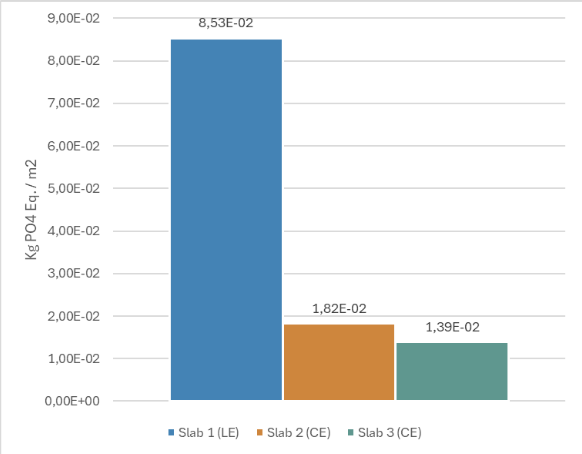
(d) Ozone Layer Depletion Potential



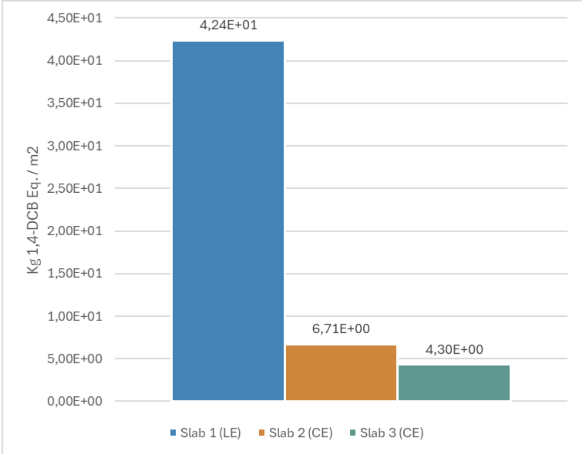
(e) Photochemical Oxidation Potential



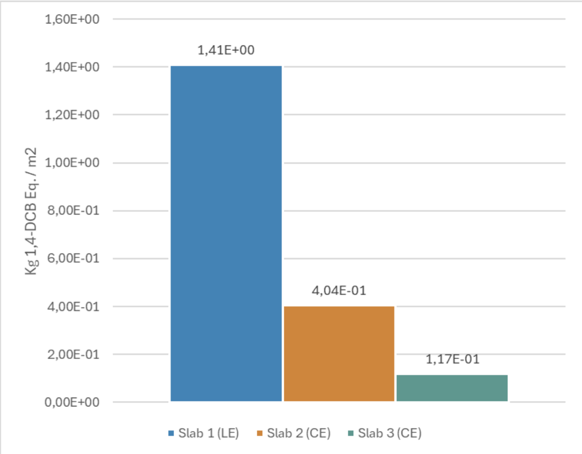
(f) Acidification Potential



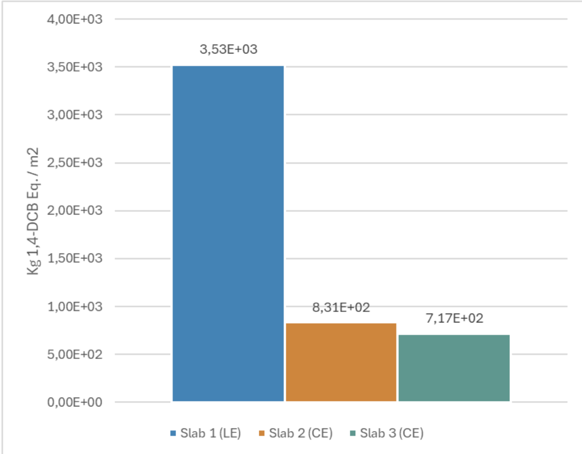
(g) Eutrophication Potential



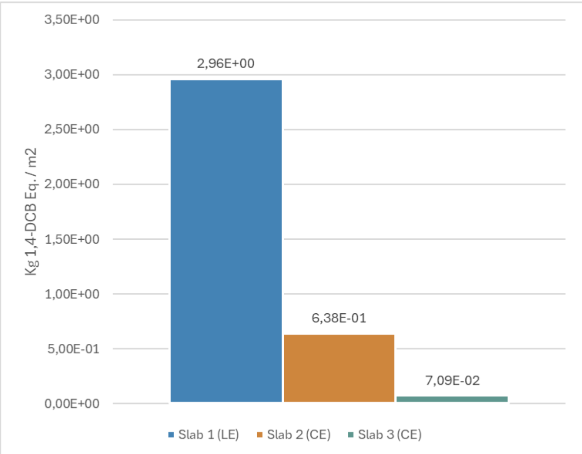
(h) Human Toxicity Potential



(i) Freshwater Aquatic Ecotoxicity Potential



(j) Marine Aquatic Ecotoxicity Potential



(k) Terrestrial Ecotoxicity Potential

(l) Environmental Cost Indicator

Figure 6.3: Environmental Impact over Three Life Cycles for Set A1

6.2. Impact of Degradation Factors

This section explores the influence of degradation factors on the structural integrity and environmental impact of floor systems. Specific attention is given to steel corrosion and concrete compressive strength reduction, as detailed in earlier discussions. The analysis will clarify how these factors affect the lifespan and performance of different slab types.

6.2.1. Steel Corrosion

This subsection investigates the impact of steel corrosion on floor systems, specifically focusing on how corrosion by carbonation affects structural integrity across multiple life cycles. Steel corrosion can significantly compromise the structural performance, necessitating interventions to maintain safety and functionality. In the study, by the second life cycle, the corrosion had progressed to a point where the structural integrity of the slab was compromised. To address this, a steel plate bonding technique was employed, as discussed in Chapter 2.3. This intervention involved the addition of steel plates to enhance the slab's bending capacity, adding an environmental load of 3.26 kg/m² in the second life cycle. This measure ensured that the structural integrity was preserved until the end of the third life cycle, highlighting the critical role of timely maintenance and retrofit strategies in extending the lifespan of structural components.

The environmental impact results for Slab 2, comparing scenarios with and without intervention, provide critical insights into the relationship between structural performance and environmental sustainability. The intervention to address steel corrosion, implemented through steel plate bonding, leads to measurable increases in key environmental impact categories. Notably, the Global Warming Potential (GWP) increases by 6.8% (from 32.2 to 34.4 kg CO2-equivalent), while the Depletion of Abiotic Resources (fossil fuels) rises by 8.9%, reflecting the significant resource and energy demands of retrofitting. Furthermore, the 17.3% increase in Human Toxicity Potential (HTP) highlights the environmental burden of introducing new materials, such as steel plates, into the life cycle.

These results emphasize the importance of addressing degradation factors, particularly corrosion, in MLCA. Although interventions like steel plate bonding are critical for maintaining structural integrity and enabling reuse, they introduce significant environmental costs that can offset some of the sustainability benefits associated with circular economy approaches.

6.2.2. Concrete Strength Reduction

The effect of reduced concrete compressive strength on floor systems is considered less critical in terms of structural impact. As detailed in Chapter 2.2, the redesign of the slabs did not necessitate adjustments due to reduced compressive strength. The primary reason is that the design of these slabs is predominantly governed by the tensile forces carried by the steel reinforcement rather than the compressive strength of the concrete. For simply supported slabs, where bending moment is the governing failure mode, the tensile side of the slab is crucial, and the steel reinforcement plays a vital role. Consequently, even with a reduction in concrete strength, the overall structural performance remains largely unaffected, underscoring the importance of reinforcement in managing loads and maintaining integrity under varied conditions.

6.3. Sensitivity Analysis

This section addresses the uncertainties associated with various assumptions and methodological choices made during this study by conducting a sensitivity analysis. This analysis evaluates the impact of variations in key parameters on the environmental impact assessments. Specifically, it examines the rate of steel corrosion, the allocation method used in life cycle assessments, and the markup percentage for Category 3 materials.

The analysis compares the baseline scenario established in the study with alternative scenarios where these parameters are adjusted. The focus is on crucial environmental impact categories relevant to the construction industry: Environmental Cost Indicator (ECI), Acidification Potential (AP), Eutrophication Potential (EP), Global Warming Potential (GWP), Human Toxicity Potential (HTP), and Ozone Depletion Potential (ODP). Tables in each subsection will present these comparisons, illustrating how changes in assumptions can influence the environmental impact profiles of the studied slab types.

6.3.1. Corrosion Rate

The corrosion rate of reinforcement in slabs can vary significantly depending on environmental conditions and the quality of construction materials. This sensitivity analysis investigates how different corrosion rates (i_{corr}) influence the structural capacity and reuse potential of slabs across multiple life cycles.

A sensitivity analysis was conducted using corrosion current density values ranging from 0.1 to $1.0\,\mu\text{A}\,\text{cm}^{-2}$. The bending moment (BM) unity checks provide insights into whether structural interventions are required to maintain the integrity of Slabs 2 and 3, which follow a circular building economy, across their respective life cycles. Slab 1, representing a linear economy, does not require reuse; thus, BM values are not applicable for t_2 and t_3.

At the reference corrosion rate ($i_{\text{corr}} = 0.3836$), Slab 2 exceeds the critical unity check value of 1.0 by t_2 (1.012), necessitating structural intervention. By t_3, this increases further to 1.188, indicating a significant loss of structural capacity. In contrast, Slab 3 maintains a unity check below 1.0 at t_2 (0.834) and only marginally exceeds it by t_3 (1.042), reflecting greater resilience to corrosion under typical conditions.

Lower corrosion rates ($i_{\text{corr}} = 0.1$ and $i_{\text{corr}} = 0.2$) result in both slabs remaining within acceptable structural limits without exceeding a unity check of 1.0, even at t_3. However, as corrosion rates increase ($i_{\text{corr}} = 0.6$ and $i_{\text{corr}} = 0.8$), Slab 2 exhibits substantial degradation, with unity checks at t_2 rising to 1.153 and 1.310, and further escalating to 1.512 and 1.934 by t_3. Slab 3 demonstrates better performance under severe conditions, staying below 1.0 at t_2 and only slightly exceeding it at t_3 (e.g., 1.042 at $i_{\text{corr}} = 0.8$).

The smaller effect of corrosion on Slab 3 can be attributed to its design, which incorporates less reinforcement compared to Slab 2. This is because the steel sheet in Slab 3 contributes significantly to its bending moment capacity, reducing its reliance on traditional reinforcement bars. This design advantage limits the extent of structural degradation caused by reinforcement corrosion.

These findings underscore the critical role of accounting for degradation factors, particularly corrosion, in lifecycle assessments of reusable slabs. While circular economy principles enhance sustainability, they require careful planning to mitigate structural degradation over time. Slab 3, with its improved resistance to corrosion, demonstrates reduced reliance on intervention measures compared to Slab 2, highlighting the importance of material selection and design strategies in extending structural lifespan and maximizing sustainability benefits.

Table 6.4: Bending Moment Unity Checks for Different Corrosion Rates (i_{corr})

Time	$i_{\text{corr}} = 0.1$			$i_{\text{corr}} = 0.2$		
	Slab 1	Slab 2	Slab 3	Slab 1	Slab 2	Slab 3
t_0	0.782	0.817	0.803	0.782	0.817	0.803
t_1	0.791	0.831	0.805	0.800	0.845	0.807
t_2	-	0.862	0.810	-	0.911	0.817
t_3	-	0.895	0.815	-	0.985	0.829

Time	$i_{\text{corr}} = 0.3836$			$i_{\text{corr}} = 0.6$		
	Slab 1	Slab 2	Slab 3	Slab 1	Slab 2	Slab 3
t_0	0.782	0.817	0.803	0.782	0.817	0.803
t_1	0.816	0.872	0.811	0.838	0.905	0.816
t_2	-	1.012	0.834	-	1.153	0.858
t_3	-	1.188	0.864	-	1.512	0.931

6.3.2. Allocation Method

This study primarily employed the cut-off (100:0) approach for life cycle assessments, which allocates the full environmental impact to the initial life cycle of the material and assigns no production burden to subsequent life cycles. To examine how different allocation methods affect the environmental impact distribution, two additional methods were analyzed: the End-of-Life (EoL) (0:100) approach and the distributed allocation method. While the total ECI across all three life cycles remains consistent, these methods redistribute the environmental cost differently across the life cycles.

The cut-off approach attributes the entire environmental cost to the first life cycle, encouraging immediate reuse by eliminating any production burden for later cycles. Conversely, the EoL approach shifts the burden entirely to the final life cycle, which can promote end-of-life strategies such as reuse. The distributed method divides the environmental cost equally among all life cycles, offering a balanced allocation but potentially underestimating the immediate benefits of reuse.

The table below illustrates the distribution of the Environmental Cost Indicator (ECI) across the three life cycles for each allocation method:

Table 6.5: Environmental Cost Indicator (ECI) Across Allocation Methods

ECI	Reference Scenario Cut-Off (100:0)			Allocation Method EoL (0:100)			Allocation Method Distributed			Unit
	Slab 1	Slab 2	Slab 3	Slab 1	Slab 2	Slab 3	Slab 1	Slab 2	Slab 3	
First LC	€ 4.34	€ 3.18	€ 3.09	€ 4.34	- € 0.02	- € 0.74	€ 4.34	€ 1.34	€ 1.15	€ / m²
Int. LC	€ 4.34	- € 0.02	- € 0.74	€ 4.34	- € 0.02	- € 0.74	€ 4.34	€ 1.02	€ 0.27	€ / m²
Last LC	€ 4.34	€ 0.21	- € 0.67	€ 4.34	€ 3.41	€ 3.15	€ 4.34	€ 1.02	€ 0.27	€ / m²
Total	€ 13.02	€ 3.38	€ 1.69	€ 13.02	€ 3.38	€ 1.69	€ 13.02	€ 3.38	€ 1.69	€ / m²

The choice of allocation method affects how environmental impacts are distributed over the life cycles. The cut-off approach emphasizes reuse by assigning the entire burden to the first life cycle. The EoL method encourages end-of-life solutions by allocating the burden to the final cycle. In contrast, the distributed method balances the impact across all life cycles, offering a neutral perspective but potentially reducing the immediate drive for reuse or recycling.

6.3.3. Category 3 mark-up

The default 30% markup for Category 3 materials, as recommended by NMD guidelines, will be tested against both higher and lower markups. This analysis aims to assess how these variations might affect the environmental cost indicators.

Table 6.6: Category 3 Data Sensitivity Analysis

Sensitivity Mark-up Analysis					
Category	**Ref. Scenario (30%)**	**-10% Reduction**	**+10% Increase**	**-20% Reduction**	**Unit**
GWP	14.6	13.5	15.7	12.5	Kg CO2 Eq / m²
ODP	1.63E-06	1.51E-06	1.75E-06	1.39E-06	Kg CFC-11 Eq / m²
AP	8.45E-02	7.82E-02	9.08E-02	7.19E-02	Kg SO2 Eq / m²
ECI	€1.68	€1.56	€1.81	€1.43	€ / m²

The analysis reveals that reducing the markup to 10% decreases the Global Warming Potential (GWP) by 14.4% (from 14.6 to 12.5 kg CO_2-eq/m²) and the Environmental Cost Indicator (ECI) by 14.9% (€1.68 to €1.43 per m²). Conversely, increasing the markup to 40% results in a 7.5% rise in GWP and a 7.7% increase in ECI. These variations underscore the significant influence of the markup assumption on the environmental impact outcomes.

This highlights the importance of improving data quality for Category 3 materials. If Category 1 or 2 data were available for Slab 3, the environmental performance might either improve due to more precise data or worsen if higher impacts are revealed by more reliable datasets.

6.4. Reuse Management: Feasibility and Compatibility

The reuse of slabs across multiple life cycles offers significant environmental benefits but presents substantial challenges in terms of management and compatibility. A robust system for tracking, standardization, and regulation is essential to ensure slab reuse. This section explores the feasibility of managing slabs over a 150-year timeframe and addresses issues related to varying slab types, sizes, connections, and regulations.

Feasibility of Reuse

Timing and Inventory Management

A primary challenge in multi-life cycle reuse is ensuring that slabs are accessible when needed. Over three life cycles spanning 150 years, slabs may be deconstructed at different times and stored for varying periods. An inventory management system, supported by material passports, is essential to track slabs and ensure their usability across projects. Material passports would provide detailed information about slab specifications, including dimensions, load capacity, and material properties, enabling efficient matching with future construction requirements [82, 83, 84]. A centralized digital platform could catalog reusable slabs, storing information about their dimensions, load capacity, and material properties in material passports. This would facilitate the identification and procurement of compatible slabs for construction projects. Advanced algorithms could further enhance this system by matching stored slabs to upcoming designs based on factors such as load requirements, dimensions, and construction timelines.

In the Netherlands, platforms like Madaster [85] and Insert [86] already facilitate the registration of material passports for structural elements, although their coverage of slabs remains limited. Similarly, the Nationale Bruggenbank [87] catalogs reusable bridges, while the HTS (Heyne Tillett Steel) Stockmatcher [88] in the United Kingdom supports the reuse of steel elements. These examples demonstrate how a similar system for slabs could ensure effective management and reuse across multiple life cycles.

Plausibility of Multi-Life Cycle Reuse

Managing slabs for reuse over 150 years requires addressing practical concerns about storage, ownership, and availability. Slabs removed from buildings need to be stored in facilities where they are protected from degradation, such as corrosion or cracking, during the transition phase between the deconstruction of the old building and the construction in the new building [83]. Proper storage infrastructure must be developed to ensure the long-term usability of slabs. Additionally, establishing clear ownership of reusable slabs is critical. This process would require collaboration among stakeholders, including building owners, demolition contractors, and reuse facilities.

In the Netherlands, a protocol for the reuse of hollow-core slabs has been developed by SKG-IKOB Certification [89]. This protocol aims to verify the suitability of hollow-core slabs from demolished buildings for future applications. Expanding such guidelines to encompass all slab types would significantly enhance the potential for reuse across the construction industry.

Comparability of Slab Types, Sizes, and Connections

Compatibility Across Designs

Variations in slab dimensions and connection systems present significant barriers to reuse. Slabs designed for one building may not fit seamlessly into another due to differences in slab dimensions, including length, width, and thickness, as well as the type of connection method used. Addressing these challenges requires the introduction of standard slab sizes, which would simplify reuse by ensuring compatibility across projects. Alternatively, grid sizes in new buildings could be adapted to fit available slabs. Moreover, prioritizing connection systems that can be safely disassembled without causing damage to slabs during deconstruction is crucial. Examples include bolted connections or modular systems that maintain the structural integrity of slabs. Designing for disassembly during the design phase enhances the potential for effective reuse and integration of components in subsequent applications, supporting the broader principles of circular construction [82].

Regulatory Challenges

The lack of universal regulations governing slab reuse exacerbates compatibility issues. Currently, no standardized guidelines exist for designing slabs with reuse in mind, leading to inconsistencies in their manufacture, connection, and storage. Governments and industry bodies should develop comprehensive guidelines covering slab dimensions, connection systems, and documentation. Collaboration among engineers, manufacturers, and policymakers is essential to align practices with reuse goals.

Recommendations for Managing Feasibility and Compatibility

- **Expand the Reuse Protocol for All Slabs:** Building on the existing protocol for hollow-core slabs, guidelines should be developed to cover other slab types, ensuring consistent practices for their reuse.
- **Develop a Digital Slab Inventory System:** Inspired by the HTS Stockmatcher in the United Kingdom [88], a centralized database could track slabs from production to demolition and beyond. This system should include information on dimensions, structural properties, and current locations. Extending this system to all structural elements would enhance reuse potential across the construction industry.
- **Standardize and Mandate Material Passports:** Material passports should become a mandatory part of building design, ensuring that all structural elements are cataloged for future reuse. Harmonizing these passports to include essential information for reuse would facilitate their integration into future projects [82, 84].
- **Design for Disassembly:** Slabs should be designed for disassembly with demountable connections to ensure compatibility with future construction projects. This would prevent damage during deconstruction and improve reuse efficiency [82].

Conclusion

The feasibility and compatibility of reusing slabs over three life cycles are critical to the success of this approach. The protocol for reusing hollow-core slabs in the Netherlands provides a valuable foundation, but a more comprehensive framework covering all slab types is needed. Effective management strategies, such as inventory systems and standardization, are essential to ensure slabs remain usable and compatible over a 150-year timeframe. Addressing these challenges through practical measures and regulatory frameworks will increase the reuse potential of slabs, contributing to a more sustainable construction industry.

6.5. Implications for Sustainable Construction

The results of this study underscore the significant environmental advantages of adopting a circular economy approach in construction. The analysis demonstrates that reusing materials, as seen with Slab 2 (Hollow-Core Slab) and Slab 3 (Deep Deck Composite Slab), leads to reduced environmental impacts across multiple life cycles, particularly in areas such as Global Warming Potential (GWP) and Depletion of Abiotic Resources. These findings suggest that the construction industry can significantly reduce its environmental footprint by designing for material reuse and extending the lifecycle of building components.

However, the need for interventions, such as strengthening Slab 2 due to reinforcement corrosion, highlights the challenges associated with reusing materials. While the circular economy approach remains beneficial, minimizing the need for such interventions through better design strategies is crucial. Additionally, in practice, it is important to consider the deconstruction phase of the building. During deconstruction, materials may be damaged due to handling, transport, or temporary storage between the donor building and the new project site. These factors can influence the overall sustainability of reused materials and should be factored into the decision-making process to ensure that the benefits of reuse are not compromised.

Incorporating the lessons learned from this study can help guide industry stakeholders, including architects, engineers, and policymakers, towards more sustainable practices. This includes encouraging the reuse of building materials, integrating long-term life cycle thinking into design and material selection processes, and considering the environmental impact of maintenance and intervention measures over the lifespan of a building.

6.6. Summary

This chapter analyzed the environmental impacts of different floor systems across multiple life cycles, focusing on traditional versus circular economy approaches. Slab 3 (Deep Deck Composite Slab), optimized for reuse, consistently demonstrated the lowest environmental impacts in most categories, including Global Warming Potential and Depletion of Abiotic Resources. Slab 2 (Hollow-Core Slab), while also benefiting from reuse, required interventions like strengthening due to reinforcement corrosion, adding to its environmental cost. Slab 1 (Cast-In-Situ Concrete Slab), representing the linear economy model, exhibited the highest overall impacts.

The study incorporated reuse management strategies into the analysis, emphasizing the importance of material tracking systems, such as digital inventories and material passports, to facilitate reuse across life cycles. Making material passports mandatory in building guidelines is critical to ensuring that essential information about slab specifications, such as dimensions, load capacity, and material properties, is available for future reuse. Moreover, prioritizing demountable connections in the design phase is essential to preserve slab integrity during deconstruction and enhance compatibility with future construction projects.

The results also addressed degradation factors, with reinforcement corrosion posing significant challenges that necessitated structural interventions. These findings underline the importance of designing floor systems for durability and reuse to maximize sustainability benefits.

In conclusion, this chapter reinforces the advantages of circular economy principles in construction, highlighting the need for robust reuse management strategies and long-term life cycle planning. By integrating reuse considerations into design, construction, and regulation, the construction industry can significantly enhance its sustainability performance.

7

Conclusion & Discussion

This chapter begins by summarizing the findings of the study through answers to the research subquestions and the main research question. It then discusses the limitations of the study and concludes with practical recommendations for industry applications and suggestions for future research. This structure provides a comprehensive assessment of the study's contributions and its broader implications.

7.1. Conclusion

To answer the research questions, three concrete-based floor systems were selected to represent diverse construction methods commonly used in the Netherlands: cast in-situ concrete slabs, prefabricated hollow core slabs, and deep deck composite slabs. These systems were designed to achieve comparable structural performance for office loading conditions in steel-framed buildings. Key considerations such as reinforcement corrosion and concrete strength reduction were accounted for to ensure long-term durability and reuse potential.

The structural and environmental performance of these systems was assessed across three life cycles. Additionally, the feasibility of reuse and demountability was evaluated to identify practical measures that support sustainable design. The following sections present the answers to the research subquestions and provide a comprehensive response to the main research question.

7.1.1. Answers to the Research Subquestions

In this section the research subquestions that were stated in this study will be answered.

”Which floor systems can be selected for analysis based on the most common floor types for buildings in the Netherlands?”

The selection of floor systems for this study was based on their widespread use in the Netherlands and their representation of diverse construction methods. To ensure a comprehensive analysis, three concrete-based floor systems were chosen: the cast-in-situ concrete slab, the prefabricated hollow core slab, and the deep deck composite slab. These systems were selected based on their structural characteristics, prevalence in Dutch construction, and alignment with research trends identified in academic publications (Section 2.1). Table 7.1 provides an overview of their key attributes and reasons for inclusion.

Table 7.1: Overview of Selected Floor Systems

Floor System	Key Characteristics	Reason for Selection
Cast-In-Situ Concrete Slab	Highly adaptable; robust strength; allows complex layouts	Traditional floor system, non-demountable
Prefabricated Hollow Core Slab	Lightweight; reusable; efficient material use; high fire resistance; long spans; rapid installation	Prefabricated variant, demountable
Deep Deck Composite Slab	Combines steel and concrete; excellent material efficiency; supports longer spans; rapid installation	Composite slab; demountable

This selection ensures that the study incldudes traditional, prefabricated, and composite construction methods. Cast-in-situ slabs are highly versatile and robust but are also labor-intensive and non-demountable. Hollow core slabs are lighter, reusable, and ideal for rapid construction and long spans. Deep deck composite slabs, combining steel and concrete, provide excellent material efficiency and adaptability, particularly for sustainable and demountable applications.

Together, these floor systems provide a strong foundation for evaluating the structural and environmental performance of floor systems commonly used in the Netherlands.

”What are the performance characteristics of each floor system for steel-based buildings in terms of material use, strength, and stiffness?”

The performance characteristics of the three floor systems (cast-in-situ concrete slab, hollow core slab, and deep deck composite slab) were evaluated based on material use, strength, and stiffness under uniform office loading conditions in Chapter 3. These floor systems were designed to fit a 5.4 by 2.5-meter grid and were subjected to office loading conditions. To ensure comparability, the designs were optimized to achieve a unity check of 0.80, balancing structural capacity and efficiency (Section 3.1). The unity check is defined as:

$$\text{Unity Check} = \frac{M_{\text{Ed}}}{M_{\text{Rd}}} = 0.80 \tag{7.1}$$

where M_{Ed} is the design bending moment due to applied loads, and M_{Rd} is the bending moment resistance of the slab. Table 7.2 summarizes the key quantitative data.

- **Material Use:** The cast-in-situ slab is the most material-intensive, requiring 360.0 kg/m² of concrete and 6.17 kg/m² of reinforcement. The hollow core slab reduces material usage significantly, with 252.15 kg/m² of concrete, 1.71 kg/m² of reinforcement, and 1.54 kg/m² of prestressed tendons. The deep deck composite slab is the most efficient, requiring 242.40 kg/m² of concrete, only 0.37 kg/m² of reinforcement, and an additional 13.0 kg/m² for the steel sheeting.
- **Strength:** All slabs achieve bending moment unity checks below 1.0, with initial values of 0.78 (cast-in-situ), 0.82 (hollow core), and 0.80 (deep deck composite). The hollow core slab, however, exhibits an increased unity check exceeding 1.0 in subsequent life cycles due to reinforcement corrosion, which weakens the prestressing tendons and reinforcement bars critical for its load-bearing capacity, necessitating intervention. In contrast, the deep deck composite slab relies less on internal reinforcement and more on the composite action between the steel sheeting and concrete, making it more resilient to corrosion-related degradation over time. As a result, the deep deck composite slab maintains a bending moment unity check of 0.88 at the end of its service life, remaining within acceptable structural limits across all life cycles.

- **Stiffness:** Deflection unity checks are below 1.0 for all slabs, with values of 0.38 (cast-in-situ), 0.46 (hollow core), and 0.53 (deep deck composite). The cast-in-situ slab demonstrates the highest stiffness, but all designs meet serviceability criteria.

The performance characteristics of the selected floor systems, including material quantities and unit weights, are summarized in Table 7.2. The cast-in-situ slab has the highest unit weight (3.75 kN/m²) due to its higher concrete and reinforcement content, making it the most material-intensive option. In contrast, the hollow core slab (2.68 kN/m²) and the deep deck composite slab (2.67 kN/m²) have significantly lower unit weights. This reduction in self-weight is achieved through the use of voids and composite action, respectively, demonstrating their material efficiency and suitability for lightweight construction.

Table 7.2: Performance Characteristics and Unit Weight of Selected Floor Systems

Criterion	Cast-In-Situ	Hollow Core	Deep Deck Composite	Unit
Concrete Volume	360.00	252.15	242.40	kg/m²
Reinforcement	6.17	1.71	0.37	kg/m²
Tendons	-	1.54	-	kg/m²
Steel Sheet	-	-	13.0	kg/m²
Unity Check (Bending)	0.78	0.82	0.80	-
Unity Check (Shear Force)	0.40	0.15	0.46	-
Unity Check (Deflection)	0.38	0.46	0.53	-
Unit Weight (Self-Weight)	3.75	2.68	2.67	kN/m²

The lower unit weight of the hollow core slab and deep deck composite slab makes them advantageous for projects where reduced self-weight can minimize foundation loads or allow for larger spans without additional support. This efficiency in self-weight highlights the potential for both slabs in sustainability-focused projects, particularly where structural optimization is a priority.

The hollow core slab demonstrates significant material efficiency but requires strengthening for reuse due to reinforcement corrosion. The deep deck composite slab combines material efficiency with resilience, making it the most sustainable option for multi-life cycle applications. In contrast, the cast-in-situ slab, while robust, is material-intensive, making it less suitable for projects prioritizing resource efficiency.

”What factors need to be considered in a Multi-Life Cycle Assessment of different floor systems?”

A Multi-Life Cycle Assessment (MLCA) evaluates the environmental impact of floor systems across multiple life cycles, considering factors such as material degradation, interventions, and reuse potential. In this study, three critical considerations were identified for a comprehensive MLCA:

- **Degradation Factors (Section 3.5):** Two key degradation mechanisms were evaluated: reinforcement corrosion and concrete compressive strength reduction.
  - Corrosion due to carbonation reduced the effective reinforcement area in all slabs, impacting their bending capacity. For the hollow core slab (Slab 2), this reduction increased the bending moment unity check to 1.01 after the second life cycle and 1.17 after the third life cycle, necessitating an intervention. Steel plate bonding was implemented, adding 2.36 kg/m² of steel in the second life cycle (Section 3.7.3). Table 7.3 summarizes the unity checks for reinforcement corrosion over the life cycles.

Table 7.3: Unity Checks Considering Reinforcement Corrosion Over Life Cycles

Time	Slab 1			Slab 2			Slab 3		
	BM	**SF**	**Defl**	**BM**	**SF**	**Defl**	**BM**	**SF**	**Defl**
t_0	0.782	0.403	0.380	0.817	0.146	0.288	0.803	0.460	0.528
t_1	0.816	0.403	0.380	0.872	0.147	0.288	0.811	0.471	0.528
t_2	-	-	-	1.012	0.150	0.288	0.834	0.507	0.528
t_3	-	-	-	1.188	0.154	0.288	0.864	0.577	0.528

– Concrete compressive strength reduction had no significant impact on the structural performance of any slab over three life cycles. For example, the unity check for bending moment remained unchanged for all slabs at values below 1.0, confirming no adjustments were required (Section 3.7.2). Table 7.4 provides unity checks for compressive strength reduction.

Table 7.4: Unity Checks Considering Compressive Strength Reduction Over Life Cycles

Time	Slab 1			Slab 2			Slab 3		
	BM	**SF**	**Defl**	**BM**	**SF**	**Defl**	**BM**	**SF**	**Defl**
LC1	0.782	0.403	0.380	0.817	0.146	0.288	0.803	0.460	0.528
LC2	-	-	-	0.817	0.176	0.304	0.803	0.502	0.534
LC3	-	-	-	0.817	0.213	0.319	0.803	0.547	0.539

- **Reuse Management: Feasibility and Compatibility (Section 6.4):** Managing slabs over multiple life cycles involves addressing challenges related to inventory management, material passports, and standardization. Ensuring standardized slab dimensions and incorporating design for disassembly practices increase the feasibility of reuse in the construction industry.

By addressing these factors quantitatively, the MLCA provides a comprehensive framework for evaluating the environmental impact of floor systems over their entire service life. This approach highlights opportunities for sustainability improvements and emphasizes the importance of considering factors that could play a role when reusing slabs over multiple life cycles, such as degradation mechanisms like corrosion and the feasibility of reuse through effective management practices.

”What are the differences in environmental impact outcomes among the different floor systems?”

The environmental impact outcomes of the three floor systems, Cast-In-Situ Concrete Slab (Slab 1), Hollow Core Slab (Slab 2), and Deep Deck Composite Slab (Slab 3), exhibit notable differences across various impact categories. This analysis was conducted in Chapter 5.3 and further discussed in Section 6.1. Slab 1, which follows a linear economy approach, consistently shows the highest environmental burdens due to its traditional construction methods and reliance on high material quantities, particularly concrete. This is reflected in its elevated values for Global Warming Potential (GWP), Depletion of Abiotic Resources (fossil fuels), and Environmental Cost Indicator (ECI), as demonstrated in the environmental impact results.

Slab 2 benefits from a circular economy approach that incorporates material reuse, resulting in substantial reductions in environmental impacts when compared to Slab 1. For instance, GWP is reduced by 72.11%, and ECI is lowered by 78.06% relative to Slab 1. However, due to reinforcement corrosion, Slab 2 requires strengthening interventions during reuse, introducing additional environmental burdens in categories such as Human Toxicity Potential (HTP) and Freshwater Aquatic Ecotoxicity Potential (FAETP). Despite these additional impacts, Slab 2 performs significantly better overall than Slab 1, highlighting the environmental benefits of adopting a circular building economy.

Slab 3 consistently outperforms both Slab 1 and Slab 2 across most environmental impact categories. Its composite design, which combines a steel sheet with a concrete topping, reduces material usage and avoids the need for interventions over multiple life cycles. As a result, Slab 3 achieves the lowest values for GWP and ECI, with reductions of 87.19% and 87.10%, respectively, compared to Slab 1. Slab 3 also demonstrates superior performance relative to Slab 2, achieving reductions of 54.09% in GWP and 41.26% in ECI. This highlights its advantages in material efficiency and sustainability, despite a slightly higher impact in Acidification Potential (AP) compared to Slab 2.

To provide a clear overview of these differences, Table 7.5 presents the percentage differences across the slabs for key environmental impact categories. These results emphasize the superior environmental performance of Slab 3 and underscore the trade-offs involved in using Slab 2, which requires additional interventions for reuse. The findings further highlight the inefficiencies of Slab 1's linear approach, reinforcing the advantages of circular economy principles in achieving long-term sustainability.

Table 7.5: Percentage Differences Across Slabs (Set A1)

Category	**Slab 2 vs Slab 1 (%)**	**Slab 3 vs Slab 1 (%)**	**Slab 3 vs Slab 2 (%)**
ADP-minerals&metals	-73.54	-96.54	-86.89
ADP-fossil	-77.23	-87.03	-43.03
GWP-total	-72.11	-87.19	-54.09
ODP	-75.74	-83.84	-33.47
POCP	-89.36	-91.96	-24.52
AP	-82.65	-82.21	+2.55
EP	-78.66	-83.72	-23.63
HTP	-84.17	-89.86	-35.88
FAETP	-71.34	-91.70	-70.98
MAETP	-76.46	-79.69	-13.74
TETP	-78.44	-97.60	-88.89
ECI	**-78.06**	**-87.10**	**-41.26**

Among the key differences, the Acidification Potential (AP) is the only category where Slab 3 performs slightly worse than Slab 2, with a 2.55% higher value. This difference is primarily due to the production of the galvanized steel sheeting used in Slab 3, which emits substances that contribute to acidification during its manufacturing process. In contrast, Slab 2 requires additional strengthening but avoids emissions related to steel sheeting.

The Terrestrial Ecotoxicity Potential (TETP) shows the largest reduction (97.60%) when comparing Slab 3 to Slab 1. This significant difference arises from the avoidance of large quantities of concrete in Slab 3, which reduces the leaching of toxic substances associated with concrete production and disposal. The composite action between steel and concrete minimizes the overall use of environmentally harmful materials, contributing to Slab 3's superior performance in this category.

The Terrestrial Ecotoxicity Potential (TETP) shows the largest reduction (97.60%) when comparing Slab 3 to Slab 1. This significant difference is influenced by the avoidance of large quantities of cast-in-situ concrete, which has a notably high TETP per cubic meter compared to other materials in the floor systems (Appendix D). By reducing the concrete volume and combining it with a steel sheeting layer, Slab 3 minimizes the contribution of materials with high TETP values.

For Depletion of Abiotic Resources (fossil fuels), Slab 3 achieves an 87.03% reduction compared to Slab 1. This large reduction reflects the reduced use of concrete, which is energy-intensive to produce, and the efficiency of the composite slab's design in minimizing resource use while maintaining structural performance.

”How can a framework be developed for assessing the environmental impact over multiple life cycles of different floor systems?”

This study developed a comprehensive framework for assessing the environmental impact of floor systems over multiple life cycles. This framework is designed to guide researchers and engineers in conducting systematic and comparable Multi-Life Cycle Assessments (MLCA) for structural systems. The steps in the framework are:

- **Establish Design Comparability:** Standardize design parameters, such as structural grid, loading conditions, and performance criteria, to ensure consistent evaluation across systems. In this framework, slabs are designed for a 5.4 x 2.5-meter grid with a bending moment unity check of 0.80 to balance structural capacity and efficiency (Section 3.1).
- **Incorporate Degradation Factors:** Identify and account for factors such as reinforcement corrosion and concrete compressive strength reduction. Where necessary, adjust designs or apply interventions to maintain structural integrity. For instance, steel plate bonding was applied to the hollow core slab in the second life cycle to address corrosion effects (Section 5.1.6).
- **Define Scope and Goals:** Clearly define the scope, system boundaries, and the functional unit. This framework uses one square meter of floor area as the functional unit, with life cycle stages ranging from production (A1–A3) to beyond life cycle (D) (Section 5.1.1).
- **Develop a Material Inventory and Choose Tools:** Quantify material requirements for all designs and select validated tools for environmental assessment. For example, this framework uses the Nationale Milieu Database (NMD) and GPR Materiaal to calculate environmental impacts (Section 5.1.2).
- **Select Environmental Impact Categories:** Align with international standards such as EN 15804 [47]. This framework incorporates Set A1 impact categories and shadow pricing to calculate Environmental Cost Indicators (ECI) for monetary representation of impacts (Section 5.1.3).
- **Determine Allocation Methods:** Use a consistent allocation method to distribute environmental burdens across life cycles. This framework employs the cut-off method, which assigns production impacts to the first life cycle and intervention impacts to subsequent cycles (Section 5.1.5).
- **Analyze and Compare Results:** Present and interpret results across key environmental impact categories. For example, in this study, the deep deck composite slab demonstrated the lowest environmental impact, while the hollow core slab required additional materials due to corrosion, increasing its environmental burden in later life cycles (Section 5.3 and 6.1).

This framework provides a robust methodology for conducting MLCA, ensuring consistency, comparability, and transparency in environmental assessments. By following the steps outlined in this framework, and referring to the referenced sections and chapters, engineers and researchers can perform a similar comparative assessment tailored to their specific context and objectives.

7.1.2. Answer to the Main Research Question

”What are the structural and sustainability performance characteristics of different floor systems used in buildings in the Netherlands when evaluated using a Multi-Life Cycle Assessment (MLCA)?”

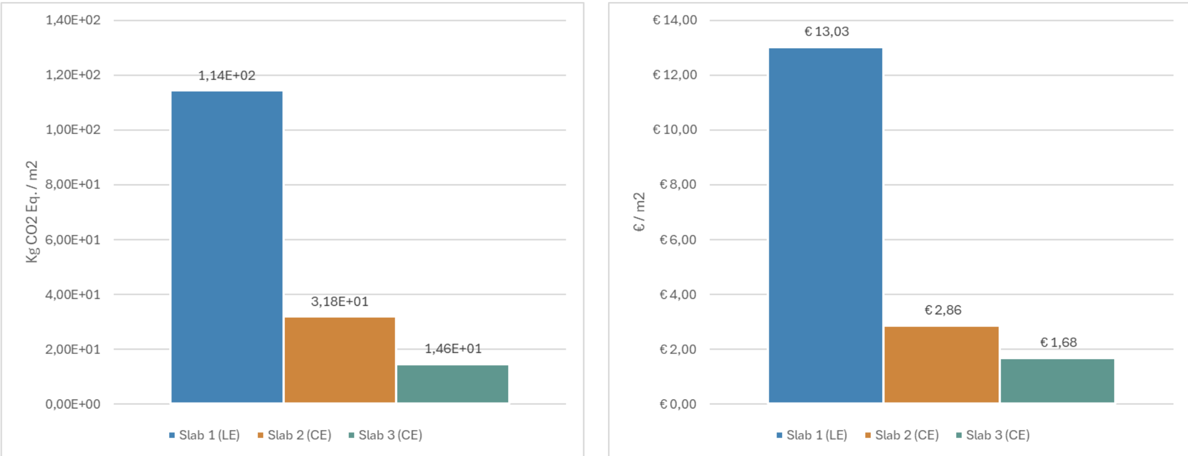
This study evaluated the structural and sustainability performance of three commonly used floor systems: Cast-In-Situ Concrete Slab (Slab 1), Hollow Core Slab (Slab 2), and Deep Deck Composite Slab (Slab 3). The analysis included assessments of material use, strength, stiffness, and environmental impact across multiple life cycles using the Multi-Life Cycle Assessment (MLCA) framework developed in this study.

Structurally, all slabs were designed to achieve comparable performance, with a bending moment unity check of 0.8. Slab 1 is versatile and highly robust but requires significant quantities of concrete, making it resource-intensive and contributing to its higher environmental impact. Slab 2, with its prefabricated design, demonstrated material efficiency and ease of installation but required strengthening measures due to reinforcement corrosion during reuse. Slab 3 combined steel and concrete for optimal material efficiency, avoiding the need for interventions, and maintained structural resilience over three life cycles.

In terms of sustainability, Slab 3 consistently outperformed both Slab 1 and Slab 2 across environmental impact categories. Its composite design minimized material use while achieving the lowest Environmental Cost Indicator (ECI) and Global Warming Potential (GWP). As shown in Table 7.5, Slab 3 achieved reductions of 87.10% in ECI and 87.19% in GWP compared to Slab 1, highlighting the benefits of its material efficiency and reuse potential.

Slab 2, while demonstrating significant improvements over Slab 1, incurred additional environmental burdens from interventions to address corrosion, particularly in categories such as Human Toxicity Potential (HTP) and Freshwater Aquatic Ecotoxicity Potential (FAETP). Despite these additional impacts, Slab 2 reduced its ECI by 78.06% and its GWP by 72.11% compared to Slab 1. These results emphasize the trade-offs involved in adopting circular economy principles for reuse. However, Slab 2's ease of installation and prefabrication remain practical advantages in construction workflows.

Slab 1, following a linear building economy model, showed consistently higher environmental impacts due to its reliance on traditional construction methods and high material consumption. Its ECI and GWP remained significantly higher than those of Slab 2 and Slab 3, underscoring the limitations of a single-use approach.



(a) Global Warming Potential

(b) Environmental Cost Indicator

Figure 7.1: Comparison of GWP and ECI Across Slabs Over Three Life Cycles

Figure 7.1 illustrates the comparative performance of the slabs in terms of GWP and ECI over three life cycles. These visual comparisons highlight the superior sustainability performance of the circular economy principle of Slab 2 and Slab 3 due to reuse and material efficiency.

In conclusion, this study demonstrates that adopting a circular economy approach, as seen with Slab 2 and Slab 3, offers substantial environmental benefits compared to the linear model of Slab 1. Among the analyzed systems, Slab 3 emerges as the most sustainable option, combining material efficiency with resilience and requiring no additional interventions. These findings highlight the importance of designing for reuse and minimizing interventions to achieve long-term sustainability in building construction.

Evaluating the floor systems over multiple life cycles provided a deeper understanding of their long-term performance and environmental impacts. The multi-life cycle approach captures the cumulative effects of degradation, reuse, and maintenance, highlighting trade-offs that may not be visible in single-cycle assessments. This demonstrates the necessity of multi-life cycle assessments (MLCA) to inform more robust design strategies that prioritize resource efficiency, durability, and sustainability across its intended service life and potential reuse cycles.

7.2. Limitations of the Study

This chapter examines the critical aspects of the study, including the methodologies employed and the key assumptions and limitations that influence the results. It discusses the approaches used for comparing slab designs, the challenges in assessing strength degradation and corrosion, the limitations related to structural analysis using parametric modeling, and the implications of environmental impact allocation methods. The chapter also reflects on the selection of life cycle assumptions and their relevance to the study's objectives. By addressing these topics, the discussion provides a comprehensive evaluation of the study's findings and their implications, while identifying areas for future research.

7.2.1. Comparability

When comparing the environmental impact of different slabs, it is essential to establish a reference point to ensure meaningful comparisons. Several approaches have been considered for this purpose.

One approach involves designing the slabs with the same thickness. However, this method may pose limitations in projects with constrained height requirements. Additionally, it can lead to inconsistencies, as some slabs may exhibit significantly higher resistance for the same thickness due to their material properties.

Another option is to design the slabs with the same weight. This ensures consistent imposed loads for a given function, such as office use. However, this approach also faces the challenge of varying resistance levels among different slab types, driven by differences in material characteristics.

A more effective method is to design the slabs based on the same unity check for a specific failure mode. This involves ensuring that the governing failure mode for each slab achieves a unity check value between 0.8 and 1.0. In this scenario, the bending moment capacity of the slab and the bending moment it must resist are proportional across all slab types. This approach reflects real-world practices, where slabs are designed to balance structural integrity with material efficiency, avoiding overdesign. Overdesign not only leads to unnecessary material usage but also increases construction costs and environmental impact.

7.2.2. Strength Degradation

To comprehensively assess the degradation of floor slabs over their life cycles, experimental studies at various stages, including the end of life, would ideally be conducted. However, there is a significant lack of such data, as continuous monitoring of buildings constructed in earlier decades is rare. Furthermore, each slab type would require specific experiments to yield precise results.

Given these limitations, this study focuses on material-level assessments of floor elements. While some experiments on the compressive strength of structural elements exist, they have not been conducted under uniform conditions. A key source for this research is a study on residential and office buildings, providing experimental data that closely aligns with this study's conditions. Consequently, these results have been used as the basis for the reduction values applied in this analysis.

While comprehensive life cycle data on strength degradation is limited, the chosen method provides a reasonable approximation for this study. Future research, leveraging additional experimental data, could refine these estimates and enhance the accuracy of the results.

7.2.3. Corrosion

The corrosion of steel reinforcement is influenced by several parameters, including the carbonation coefficient and the corrosion rate. Values for both parameters have been obtained from the literature. The carbonation coefficient depends on the type of exposure, and a value from a study conducted in Dhaka City was adopted. It is important to note that the carbonation coefficient may vary under different conditions and should be evaluated on a case-by-case basis.

The corrosion rate is affected by factors such as the water-to-cement ratio, exposure type, relative humidity, chloride concentration, and crack width. These parameters can lead to significant variations in corrosion rates for different scenarios. For this study, a value closely aligned with the specific case was selected, considering the minimal chloride concentration (due to indoor exposure) and the maximum allowable crack width for the slab.

These assumptions represent limitations of the study, as they may not fully account for variations in environmental and material conditions.

7.2.4. Environmental Impact Allocation in Reuse Scenarios

The choice of the cut-off method in this study directly impacts the way environmental benefits are allocated, particularly compared to other commonly used allocation approaches in building life cycle assessments. By applying the cut-off method, all production impacts are assigned to the initial project developer or first use of the building materials. This approach rewards material reuse in subsequent projects by attributing zero production burdens to later cycles, encouraging immediate reuse and recognizing the carbon savings achieved by preventing new material production.

In contrast, alternative methods such as the end-of-life method would defer production impacts to the final project developer, incentivizing design for future reuse. The distributed allocation method, on the other hand, would spread environmental impacts across all life cycles, potentially diluting the immediate savings recognized in this study.

By adopting the cut-off method, this research captures the immediate carbon reductions associated with material reuse, aligning with its focus on the current project's environmental savings. However, it is acknowledged that other allocation methods could provide different insights by considering future reuse cycles.

7.2.5. Number of Life Cycles

For this study, the number of life cycles has been set to three. This choice reflects the limited availability of data on the reuse potential of slabs across multiple cycles, making it a reasonable assumption. The three life cycles are categorized as the first, intermediate, and last, representing distinct scenarios for slab use. This framework allows for variations in slab performance and environmental impact across different reuse stages.

However, in this study, the hollow core slab demonstrated limitations in extending beyond a certain number of life cycles due to reinforcement corrosion. The embedded prestressing tendons and reinforcement bars were more susceptible to corrosion over time, which reduced the slab's load-bearing capacity and necessitated strengthening measures to ensure reuse. In contrast, the deep deck composite slab was less affected by internal reinforcement degradation due to its reliance on composite action between the steel sheeting and concrete topping, maintaining structural resilience over multiple life cycles.

The intermediate life cycle can be scaled up if the slab is reused more than twice, effectively accommodating additional life cycles beyond the three initially assumed. In the future, as more data becomes available and slab reuse becomes more widespread, incorporating additional life cycles could provide a more comprehensive understanding of long-term environmental and structural performance, particularly for slab types with varying durability challenges.

7.2.6. Structural Analysis Limitations

In this study, a parametric model was developed using Grasshopper [67] and Karamba3D [68] to facilitate efficient design iterations and allow for flexible adjustments to slab configurations. This approach enabled the rapid evaluation of different design scenarios, making it particularly useful for preliminary design stages. The integration of geometry, material properties, and loading conditions in a parametric environment streamlined the comparison of floor systems.

However, there are limitations to using Karamba3D [68] for structural analysis, particularly when modeling slabs with non-uniform or non-standard cross-sections. The software primarily supports standard uniform sections, necessitating homogenization to model complex slabs like the hollow core slab and the deep deck composite slab (Section 4.2.3). For the deep deck composite slab, the complex interaction between the steel sheeting and the concrete topping was simplified by calculating an equivalent bending stiffness to represent the combined properties of the materials. Similarly, the hollow core slab was modeled as a uniform cross-section by calculating its thickness based on the actual moment of inertia. While this homogenization process streamlines the analysis and improves computational efficiency, it may not fully capture localized effects, such as strain distributions or variations in behavior along non-standard sections.

As a result, the parametric model may not accurately reflect the detailed performance of slabs with non-uniform cross-sections. For more precise assessments of localized effects and material interactions, finite element (FE) software such as Abaqus [90] is recommended. FE software provides advanced capabilities for modeling complex geometries and evaluating local behaviors, complementing the global analysis provided by the parametric approach.

7.3. Recommendations for Further Research

Based on the findings of this study, several recommendations are proposed to advance research in the field of sustainable floor systems. These recommendations aim to address gaps and challenges related to the environmental impacts and reuse potential of floor systems. Pursuing these avenues can contribute to more sustainable construction practices, enhance environmental impact assessment methodologies, and support the transition towards a circular economy in the construction industry. The following suggestions are intended to guide researchers in exploring critical areas that can significantly impact the sustainability of floor systems:

1. **Comparative Assessment of Additional Floor Systems** Future studies should expand the comparative analysis to include a broader range of floor systems, such as cross-laminated timber (CLT), and innovative composite materials. Evaluating these additional floor types will provide a more comprehensive understanding of the environmental impacts associated with various construction methods and materials. This expanded comparison can help identify the most sustainable options across different contexts, informing architects, engineers, and decision-makers in selecting floor systems that optimize environmental performance.
2. **Detailed Analysis of Reuse Potential for Each Floor Type** A detailed analysis of the reuse potential for each specific floor type is recommended. By thoroughly examining factors such as structural integrity, degradation mechanisms, ease of disassembly, and necessary intervention techniques, researchers can better understand the feasibility and benefits of reusing these systems. This in-depth analysis would lead to more accurate environmental impact calculations and comparisons, as well as tailored strategies to enhance reuse potential. Such insights are crucial for developing effective practices that promote material reuse, thereby reducing waste and environmental burdens in the construction industry.
3. **Consideration of the Environmental Impact of Deconstruction** Research should investigate the environmental impacts associated with the processes required for reusing floor systems. Deconstruction activities can involve significant energy consumption, emissions, and waste generation, which may offset some environmental benefits of material reuse. By evaluating different deconstruction processes and their associated environmental costs, methods that minimize negative impacts while maximizing material recovery and reuse efficiency can be identified.

   Additionally, the design of connections between reused slabs and new structures is a critical factor influencing these environmental impacts. Non-demountable connections complicate disassembly, leading to increased energy use, material damage, and waste. Therefore, assessing the environmental performance of various connection designs is essential for a more holistic evaluation of reuse strategies.

4. **Application of the Proposed Strategy in Diverse Case Studies** It is advisable to apply the proposed multi-life cycle environmental impact assessment strategy to a wider range of case studies featuring varying grid sizes, building typologies, and slab dimensions. Implementing the strategy across different architectural designs and structural configurations will allow researchers to evaluate its adaptability and effectiveness in diverse contexts. Insights gained from these applications can help identify any limitations or necessary refinements to the methodology, enhancing the robustness and generalizability of the strategy and contributing to its practical applicability in the construction industry.

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A

Analytical Approach Cast In-Situ Slab

In this Appendix hand calculations of the concrete cast in-situ slab will be shown. The slab will be designed according to Eurocode 2. The design steps consist of verifications for the bending moment, vertical shear, longitudinal shear and deflection. The equations used in these calculations are derived from the book [91], which serves as the primary reference for the methods applied in this section.

A.1. Concrete Cover

The concrete cover is determined using EC2 and its national annex. In Chapter 4.4 of EC2, the formula is:

$$c_{\text{nom}} = c_{\text{min}} + \Delta c_{\text{dev}}$$

where:

$$c_{\text{min}} = \max\{c_{\text{min,b}}, c_{\text{min,dur}} + \Delta c_{\text{dur},\gamma} - \Delta c_{\text{dur,st}} - \Delta c_{\text{dur,add}}, 10\,\text{mm}\}$$

The exposure class for the concrete is classified as XC1, as it is situated in a dry climate with low air humidity inside the building, in accordance with Table 4.1 of EC2.

The structural classification is S4, which corresponds to a design life of 50 years. This classification specifies a minimum concrete cover $c_{\text{min,dur}}$ of 15 mm.

According to the national annex (NA) in Section 4.4.1.3, the deviation Δc_{dev} is 5 mm. Additionally, in Section 4.4.1.2 of the NA to EC2, the values for $\Delta c_{\text{dur},\gamma}$ and $\Delta c_{\text{dur,st}}$ are both 0 mm.

Thus, the nominal concrete cover c_{nom} is calculated as:

$$c_{\text{nom}} = 15\,\text{mm} + 5\,\text{mm} = 20\,\text{mm}$$

Thus, a concrete cover of 20 mm will be used. The same cover will also be used for the other slabs.

A.2. Load Calculation

The loads are as follows:

- **Permanent Loads:**
  - Self-weight of concrete: The unit weight of concrete is 25 kN/m³. For a slab width of 1 m and thickness of 0.15 m, the self-weight is:

$$\text{Self-weight} = 25\,\text{kN/m}^3 \times 1\,\text{m} \times 0.15\,\text{m} = 3.75\,\text{kN/m}^2$$

- **Imposed Loads:**
  - Office load: 2.5 kN/m²

A.3. Design Values for Limit States

For the Ultimate Limit State (ULS) strength calculations, the following equations [91] are used:

1. $1.35 \times q_g = 1.35 \times 3.75 = 8.44\,$kN/m^2
2. $1.2 \times q_g + 1.5 \times q_q = 1.2 \times 3.75 + 1.5 \times 2.50 = 8.25\,$kN/m^2

For the Service Limit State (SLS) calculation:

$$q_d = q_g + q_q = 3.75 + 2.50 = 6.25 \text{ kN/m}^2$$

where q_d is the sum of permanent loads and imposed loads.

These formulas are based on Eurocode 1 [62], which specifies load combinations and safety factors for buildings. Since the slab is part of an office building, categorized as a Consequence Class 2 structure according to Eurocode 1, the specified equations and load factors are applied.

A.4. Reaction Forces and Moments

The reaction forces and moments are calculated as follows:

- **Reaction Forces**: The reaction forces at each support are calculated by dividing the total load by 2, assuming a simple 2D analysis with symmetric loading.

$$R = \frac{1}{2} \times q_d \times L = \frac{1}{2} \times 8.25\,\text{kN/m}^2 \times (5.4\,\text{m}) = 22.28\,\text{kNm}$$

- **Design Bending Moment**:

$$M_d = \frac{1}{8} \times q_d \times L^2$$

  Where q_d is the ULS design load and L is the span. Using $q_d = 8.25\,$kN/m^2 and $L = 5.4\,$m:

$$M_d = \frac{1}{8} \times 8.25\,\text{kN/m}^2 \times (5.4\,\text{m})^2 = 30.1\,\text{kNm}$$

- **Shear Force**:

$$V_d = \frac{q_d \times L}{2}$$

  Using $q_d = 8.25\,$kN/m^2 and $L = 5.4\,$m:

$$V_d = \frac{8.25 \times 5.4}{2} = 22.28\,\text{kN}$$

A.5. Reinforcement Calculation

The required reinforcement is calculated using the formula [91]:

$$A_s = \frac{M_d}{f_{sd} \times 0.9 \times d}$$

Where:

- $f_{sd} = \frac{f_{sk}}{\gamma_s} = \frac{500}{1.15} = 435\,$N/mm^2
- $d = 125\,$mm
- $M_d = 30.1\,$kNm

Substituting these values:

$$A_s = \frac{30.1 \times 10^6}{435 \times 0.9 \times 125} \approx 599\,\text{mm}^2/\text{m}$$

Thus, the required reinforcement area A_s is approximately $599\,\text{mm}^2/\text{m}$.

A.6. Main and Dividing Reinforcement

With main reinforcement using diameter 10 mm and a spacing of 100 mm:

$$A_{s,\text{main}} = 784.4\,\text{mm}^2/\text{m}$$

This is sufficient for the main reinforcement. Dividing reinforcement is used perpendicular to the main reinforcement. Concrete has a transverse contraction coefficient v of 0.2, so the dividing reinforcement should be at least 20% of the main reinforcement [91]:

$$A_{s,\text{dividing}} = 0.2 \times 785.4\,\text{mm}^2/\text{m} = 150.8\,\text{mm}^2/\text{m}$$

Using ø8-300 reinforcement, which provides 168 mm²/m, is sufficient for the dividing reinforcement.

A.7. Shear Force Check

The shear stress τ_d is calculated using:

$$\tau_d = \frac{V_d}{b \times d}$$

Where:

- $V_d = 22.28\,\text{kN}$ (shear force)
- $b = 1000\,\text{mm}$ (width)
- $d = 125\,\text{mm}$ (internal lever arm)

Substituting these values:

$$\tau_d = \frac{22.28 \times 10^3\,\text{N}}{1000\,\text{mm} \times 125\,\text{mm}} = 0.178\,\text{N/mm}^2$$

The design shear strength of the concrete is calculated as follows. For concrete grade C20/25:

- **Characteristic Shear Strength** v_c is:

$$v_c = 0.6 \cdot \sqrt{f_{ck}} = 0.6 \cdot \sqrt{20} \approx 2.68\,\text{N/mm}^2$$

- **Design Shear Strength** $\tau_{c,d}$ is:

$$\tau_{c,d} = \frac{v_c}{\gamma_c} = \frac{2.68\,\text{N/mm}^2}{1.5} = 1.79\,\text{N/mm}^2$$

The calculated shear stress $\tau_d = 0.178\,\text{N/mm}^2$ is significantly less than the design shear strength $\tau_{c,d} = 1.79\,\text{N/mm}^2$, indicating that the slab design is adequate in terms of shear resistance.

A.8. Deflection Check

Deflection is checked using the formula:

$$\delta_{\text{max}} = \frac{5}{384} \cdot \frac{q_{d,\text{SLS}} \cdot L^4}{E \cdot I}$$

Where:

- $q_{d,\text{SLS}} = 6.25\,\text{kN/m}^2$ (design load at SLS)
- $L = 5.4\,\text{m}$ (span)
- $E = 30000\,\text{MPa}$ (modulus of elasticity of concrete)

The moment of inertia I is:

$$I = \frac{b \cdot h^3}{12}$$

Where:

- $b = 1000\,\text{mm}$
- $h = 250\,\text{mm}$

Substituting these values:

$$I = \frac{1000 \times (250)^3}{12} = 1.302 \times 10^9\,\text{mm}^4$$

Substituting into the deflection formula citecontabboek:

$$\delta_{\text{max}} = \frac{5}{384} \cdot \frac{6.25 \times (5400)^4}{30000 \times (1.302 \times 10^9)} \approx 3.047\,\text{mm}$$

The allowable deflection is:

$$\text{Allowable Deflection} = \frac{L}{250} = \frac{5400\,\text{mm}}{250} = 21.6\,\text{mm}$$

The calculated maximum deflection $\delta_{\text{max}} = 3.047\,\text{mm}$ is well within the allowable deflection limit of 21.6 mm, indicating that the deflection of the slab is acceptable and meets serviceability requirements.

A.9. Normal Stress Calculation

The normal stress is calculated using:

$$\sigma = \frac{M}{W} = \frac{M_{\text{Ed}}}{I/z} = 8.02\,\text{MPa}$$

A.10. Safety and Serviceability Checks

The safety checks (U.C.) for both bending and shear are calculated as follows:

Bending Utilization (U.C.)

$$U.C. = \frac{M_{\text{Ed}}}{M_{\text{Rd}}} = 0.78$$

Shear Utilization (U.C.)

$$U.C. = \frac{V_{\text{Ed}}}{V_{\text{Rd}}} = 0.40$$

Deflection Utilization (U.C.)

$$U.C. = \frac{\delta_{\text{calculated}}}{\delta_{\text{max}}} = 0.38$$

A.11. Conclusion

The cast in-situ concrete slab is designed in accordance with Eurocode 2. The following conclusions can be drawn:

- The bending moment and shear force capacity of the slab are sufficient.
- The required reinforcement area is adequate to resist the bending moments.
- The deflection of the slab under service load is well within the allowable limit.
- All safety and serviceability checks are satisfied, confirming the slab's suitability for the designed loads.

Thus, the slab design is structurally safe and serviceable under the applied loads.

B

Analytical Approach Hollow Core Slab

This section presents the design calculations for the Hollow Core Slab, focusing on the key aspects such as prestressed tendons, reinforcement, shear forces, bending moments, and deflection. The slab design follows the guidelines of Eurocode 2 (EC2). Detailed calculations, including forces, moments, and unity checks, can be found in the accompanying Excel calculations provided in Appendix E.

B.1. Load Calculation

The loads are as follows:

- **Permanent Loads:**
  - Self-weight of the slab: 2.68 kN/m²
- **Imposed Loads:**
  - Office load: 2.5 kN/m²

B.2. Design Values for Limit States

For the Ultimate Limit State (ULS) strength calculations, the following equations [91] are used:

1. $1.35 \times q_g = 1.35 \times 2.68 = 3.62\,\text{kN/m}^2$
2. $1.2 \times q_g + 1.5 \times q_q = 1.2 \times 2.68 + 1.5 \times 2.50 = 6.97\,\text{kN/m}^2$

For the Service Limit State (SLS) calculation:

$$q_d = q_g + q_q = 2.68 + 2.50 = 5.18\,\text{kN/m}^2$$

Where q_d is the sum of permanent loads and imposed loads.

B.3. Prestressed Tendons

In the design of the Hollow Core Slab, prestressed tendons are used to resist bending moments. The prestressed tendons are placed strategically, with their cross-sectional areas and prestress forces calculated to ensure efficient performance. The prestressed tendon parameters are:

$$A_{\text{tendon}} = 19.63\,\text{mm}^2, \quad A_{p,\text{bottom}} = 196.35\,\text{mm}^2, \quad A_{p,\text{top}} = 39.27\,\text{mm}^2$$

The net prestressing force is:

$$F_{p,\text{net}} = F_{p,\text{bottom}} - F_{p,\text{top}} = 157.08\,\text{kN}$$

For the detailed calculations related to the prestressed tendons, including forces and areas, please refer to Appendix E.

B.4. Reinforcement Design

In addition to the prestressed tendons, the slab design incorporates additional reinforcement to resist shear and provide overall stability. The reinforcement includes both longitudinal and transverse bars. The total reinforcement area and the material properties are calculated to ensure the slab is capable of resisting the applied moments and forces.

The reinforcement area, including spacing and diameter of reinforcement bars, is based on the required bending moment and shear forces.

B.5. Bending Moment Resistance

The total bending moment resistance of the slab is calculated by considering the contributions from both the prestressed tendons and the additional reinforcement. The calculated total bending moment resistance is:

$$M_{\text{Rd}} = M_{\text{Rd,p,only}} + M_{\text{Rd,s,only}} = 18.02\,\text{kNm} + 13.06\,\text{kNm} = 31.09\,\text{kNm}$$

The corresponding utilization check for bending moment resistance is:

$$U.C. = \frac{M_{\text{Ed}}}{M_{\text{Rd}}} = \frac{31.09}{25.39} = 0.82$$

Where $M_{\text{Ed}} = 25.39\,\text{kNm}$ is the applied bending moment.

For further details on the bending moment resistance and its contributions, refer to Appendix E.

B.6. Shear Force Calculation

Shear forces are calculated based on the applied loads, and the shear resistance of the slab is checked against the calculated shear forces. The total applied shear force is:

$$V_{\text{Ed}} = 18.81\,\text{kN}$$

The shear resistance $V_{\text{Rd,c}}$ is:

$$V_{\text{Rd,c}} = 128.94\,\text{kN}$$

The unity check for shear resistance is:

$$U.C. = \frac{V_{\text{Ed}}}{V_{\text{Rd,c}}} = \frac{18.81}{128.94} = 0.15$$

This value is well below 1, confirming that the slab can safely resist the calculated shear forces.

B.7. Deflection Calculation

Deflection is a critical design criterion to ensure that the slab does not deflect excessively under the applied loads. The calculated deflection is:

$$\delta = 6.21\,\text{mm}$$

The allowable deflection is:

$$\delta_{\text{max}} = \frac{L}{250} = 21.6\,\text{mm}$$

The unity check for deflection is:

$$U.C. = \frac{\delta_{\text{calculated}}}{\delta_{\text{max}}} = \frac{6.21}{21.6} = 0.29$$

Since the calculated deflection is well within the allowable limit, the slab meets the serviceability requirement.

B.8. Steel Plate Bonding

To enhance the strength of the slab, steel plate bonding is considered. The bonding does not significantly affect the deflection but contributes to the overall strength of the slab. The bonding area and bending moment resistance provided by the steel plate are calculated.

For further details on the steel plate bonding and its contribution to the overall bending resistance, refer to Appendix E.

B.9. Safety and Serviceability Checks

The safety checks (U.C.) for bending, shear, and deflection are calculated as follows:

Bending Utilization (U.C.)

$$U.C. = \frac{M_{\text{Ed}}}{M_{\text{Rd}}} = 0.82$$

Where: - $M_{\text{Ed}} = 25.39$ kNm is the applied bending moment. - $M_{\text{Rd}} = 31.09$ kNm is the bending moment resistance,

Shear Utilization (U.C.)

$$U.C. = \frac{V_{\text{Rd}}}{V_{\text{Ed}}} = 0.15$$

Where: - $V_{\text{Ed}} = 18.81$ kN is the applied shear force. - $V_{\text{Rd}} = 128.94$ kN is the shear resistance capacity,

Deflection Utilization (U.C.)

$$U.C. = \frac{\delta_{\text{calculated}}}{\delta_{\text{max}}} = 0.29$$

Where: - $\delta_{\text{calculated}} = 6.21$ mm is the calculated deflection, - $\delta_{\text{max}} = 21.6$ mm is the maximum allowable deflection.

B.10. Conclusion

The design calculations for the Hollow Core Slab show that the slab is structurally safe and meets all the necessary safety and serviceability requirements. Key findings include:

- The slab has sufficient bending moment resistance, with a utilization factor of 0.82, indicating that the bending capacity is adequate.
- The shear resistance is also sufficient, with a low utilization factor of 0.15, confirming that the slab can safely resist the calculated shear forces.
- The calculated deflection of 6.21 mm is well within the allowable deflection limit of 21.6 mm, ensuring that the slab meets serviceability requirements.
- The steel plate bonding enhances the slab's strength with minimal impact on deflection.

All the necessary design checks have been performed, and the slab design satisfies the Eurocode 2 requirements. For a detailed step-by-step calculation refer to Appendix E.

C

Analytical Approach Composite Slab

This appendix provides a comprehensive set of calculations for the design of a composite beam with profiled sheeting. The calculations include the determination of geometrical dimensions, material properties, and loading conditions for both construction and composite stages. Design checks are performed to assess the adequacy of the beam, considering both the construction and composite stages. These checks ensure that the beam meets the required strength and stability criteria according to design standards such as Eurocode 3 and 4. <Will be updated!>

C.1. Geometrical Dimensions

- **Steel Reinforcement**
  - Length, $L = 5.4$ m
  - Total height, $h = 270$ mm
  - Concrete cover height, $h_c = 60$ mm
  - Top width of steel sheet, $b_{\text{top}} = 425$ mm
  - Bottom width of steel sheet, $b_{\text{bottom}} = 54$ mm
  - Effective width of steel sheet, $b = 600$ mm
- **Steel Sheeting**
  - Profile height, $h_p = 210$ mm

C.2. Material Properties

- **Concrete**
  - Grade: C20/25
  - Characteristic Compressive Strength, $f_{ck} = 20$ MPa
  - Modulus of Elasticity, $E_{cm} = 30$ GPa
- **Steel Reinforcement**
  - Yield Strength, $f_{yk} = 500$ MPa
- **Structural Steel**
  - Thickness, $t = 1$ mm
  - Steel Grade: S275
  - Yield Strength, $f_y = 275$ MPa
  - Ultimate Tensile Strength, $f_u = 410$ MPa

C.3. Self-Weight of Concrete on Steel Sheeting

- **Wet Concrete:**
  - Volume: $0.101\,\text{m}^3/\text{m}^2$
  - Density: $25\,\text{kN/m}^3$
  - Self-Weight: $2.525\,\text{kN/m}^2$
- **Dry Concrete:**
  - Volume: $0.101\,\text{m}^3/\text{m}^2$
  - Density: $24\,\text{kN/m}^3$
  - Self-Weight: $2.424\,\text{kN/m}^2$

C.4. Loads During Construction Stage

- **Permanent Actions:**
  - Self-Weight of Steel Deck: $0.13\,\text{kN/m}^2$
- **Variable Actions:**
  - Construction Loading (Working Area): $0.75\,\text{kN/m}^2$
  - Wet Concrete: $2.525\,\text{kN/m}^2$
  - **Total Variable Actions:** $3.275\,\text{kN/m}^2$

C.5. Loads During Composite Stage

- **Permanent Actions:**
  - Self-Weight of Steel Deck: $0.13\,\text{kN/m}^2$
  - Dry Concrete: $2.54\,\text{kN/m}^2$
  - **Total Permanent Actions:** $2.67\,\text{kN/m}^2$
- **Variable Actions:**
  - Office Load: $2.5\,\text{kN/m}^2$

C.6. Design Value of Combined Actions for ULS

C.6.1. Construction Stage

$$\begin{aligned} q_d &= 1.2 \times 0.13\,\text{kN/m}^2 + 1.5 \times 2.5\,\text{kN/m}^2 \\ &= 0.156 + 3.75 \\ &= 3.906\,\text{kN/m}^2 \end{aligned}$$

C.6.2. Composite Stage

$$\begin{aligned} q_d &= 1.2 \times 2.67\,\text{kN/m}^2 + 1.5 \times 2.5\,\text{kN/m}^2 \\ &= 6.954\,\text{kN/m}^2 \end{aligned}$$

C.7. Design Values of Moment and Shear Forces at ULS

C.7.1. Construction Stage

$$M_{y,Ed} = \frac{q_d \times L^2}{8} = 14.24\,\text{kNm}$$

$$V_{Ed} = \frac{q_d \times L}{2} = 10.55\,\text{kN}$$

C.7.2. Composite Stage

$$M_{y,Ed} = \frac{q_d \times L^2}{8} = 25.35\,\text{kNm}$$

$$V_{Ed} = \frac{q_d \times L}{2} = 18.78\,\text{kN}$$

C.8. Bending Moment Resistance

The total bending moment resistance of the composite slab is determined by summing the contributions from both the steel profiled sheet and the reinforcement. Each component is analyzed separately to calculate its contribution to the slab's overall bending capacity.

The bending moment resistance of the steel profiled sheet is calculated to be $M_{\text{Rd,steel}} = 27.03\,\text{kNm}$. This resistance arises from the cross-sectional area, lever arm, and yield strength of the steel profile.

The reinforcement, consisting of $\phi 6$-600 bars, contributes an additional $M_{\text{Rd,reinf}} = 4.53\,\text{kNm}$ to the bending moment resistance. Together, the total bending moment resistance of the composite section is:

$$M_{\text{Rd,total}} = M_{\text{Rd,steel}} + M_{\text{Rd,reinf}} = 27.03\,\text{kNm} + 4.53\,\text{kNm} = 31.56\,\text{kNm}$$

This total resistance is compared to the applied bending moment, $M_{\text{Ed}} = 25.35\,\text{kNm}$, resulting in a unity check:

$$\text{U.C.} = \frac{M_{\text{Ed}}}{M_{\text{Rd,total}}} = \frac{25.35}{31.56} = 0.80$$

Since the unity check is less than 1.0, the composite slab safely satisfies the bending moment resistance requirements. This demonstrates that the combined contributions of the steel profiled sheet and the reinforcement provide adequate capacity to resist the applied bending moments in accordance with design standards.

C.9. Shear Force Calculation

Shear forces are calculated based on the applied loads, and the shear resistance of the slab is checked against the calculated shear forces. For the deep deck composite slab, the total applied shear force is:

$$V_{\text{Ed}} = 18.78\,\text{kN}$$

The shear resistance, $V_{\text{Rd,c}}$, considering the contribution of the steel deck and the concrete, is:

$$V_{\text{Rd,c}} = 40.84\,\text{kN}$$

The unity check for shear resistance is calculated as:

$$U.C. = \frac{V_{\text{Ed}}}{V_{\text{Rd,c}}} = \frac{18.78}{40.84} = 0.46$$

This value is significantly below 1.0, confirming that the deep deck composite slab can safely resist the calculated shear forces under the given loading conditions. The combination of the steel deck and concrete provides adequate shear resistance as required by the design standards.

C.10. Deflection

The effective bending stiffness (EI_{eff}) of the composite slab modeled as a uniform concrete slab was calculated based on the homogenization of the bending stiffnesses of the concrete and steel components. This involves computing the moments of inertia of each component and using Steiner's theorem to adjust for their respective distances from the neutral axis.

The formula used to calculate the effective bending stiffness is as follows:

$$EI_{\text{eff}} = EI_0 + E_c \cdot A_c \cdot a_c^2 + E_s \cdot A_p \cdot a_p^2$$

where:

- $EI_0 = E_c \cdot I_c + E_s \cdot I_s$ is the initial bending stiffness combining the contributions of concrete and steel without considering their vertical positions relative to the neutral axis.
- E_c and E_s are the moduli of elasticity of concrete and steel, respectively.
- A_c and A_p are the cross-sectional areas of the concrete slab and the steel profile.
- a_c and a_p are the distances from the centroids of the concrete and steel to the neutral axis of the composite section.

Substituting the values calculated earlier:

$$EI_{\text{eff}} = 5.02 * 10^{12} \text{ Nmm}^2$$

This stiffness is then used to estimate the deflection under a uniformly distributed load using the formula for a simply supported beam:

$$\delta = \frac{5qL^4}{384EI_{\text{eff}}}$$

Where:

- q is the distributed load, 5.17 kN/m
- L is the span, 5.4 m

Calculating the deflection:

$$\delta = \frac{5 \times 5170 \times (5400)^4}{384 \times 5.02 * 10^{12}} = 11.41 \text{ mm}$$

C.11. Summary of Unity Checks

This section summarizes the calculated unity checks (U.C.) for bending, shear, and deflection for both the construction and composite stages of the composite slab.

Bending Utilization (U.C.)

$$U.C. = \frac{M_{Ed}}{M_{Rd}} = 0.80$$

Where: - $M_{Rd} = 31.56$ kNm is the bending moment resistance, - $M_{Ed} = 25.35$ kNm is the applied bending moment.

Shear Utilization (U.C.)

$$U.C. = \frac{V_{Ed}}{V_{Rd}} = 0.46$$

Where: - $V_{Rd} = 40.84$ kN is the shear resistance capacity, - $V_{Ed} = 18.78$ kN is the applied shear force.

Deflection Utilization (U.C.)

$$U.C. = \frac{\delta_{\text{calculated}}}{\delta_{\text{max}}} = 0.53$$

Where: - $\delta_{\text{calculated}} = 11.41$ mm is the calculated deflection, - $\delta_{\text{max}} = 21.6$ mm is the maximum allowable deflection.

C.12. Conclusion

The design calculations for the composite slab confirm that the slab is structurally sound and meets all required safety and serviceability criteria. Key findings include:

- The bending moment utilization check shows that the slab has sufficient bending capacity, with a unity check of 0.80, indicating it is well below the allowable limit of 1.0.
- The shear utilization check confirms adequate shear capacity, also with a unity check of 0.46.
- The calculated deflection of 11.41 mm is within the permissible limit of 21.6 mm, satisfying serviceability requirements.

Overall, the composite slab design adheres to the Eurocode 3 and 4 standards, ensuring that it can safely and effectively support the required loads in both construction and composite stages. For a detailed breakdown of the calculations, refer to Appendix E.

D GPR Materiaal Data

This appendix compiles the material data obtained through the validated NMD tool, GPR Materiaal. The dataset includes environmental impact values for all elements used in the environmental impact assessment under Set A1 and A2 categories, as well as the Environmental Cost Indicator (ECI) value for each life cycle stage. This comprehensive data, retrieved from GPR Materiaal, has been integral to the environmental impact calculations for the different slabs. Table D.1 provides an overview of the GPR Materiaal content included on each page.

Table D.1: Overview of GPR Materiaal Data

Page Number	**Content Description**
105	C20/25 Concrete
106 - 111	VBI Hollow Core Slab
112	Deep Deck Composite Slab
113	Steel Reinforcement

Vloer C20/25 0% betongranulaat Raijmakers Beton Helden en Someren m2 --> m3 d = 0,21 m Cat. 1

SET A1	A1 - A3	A4 - A5	B	C	D	Total	Unit
Depletion of abiotic resources minerals and metals (ADP)	8,29E-04	4,47E-04	0,00E+00	5,00E-04	-4,60E-04	**1,32E-03**	kg Sb eq
Depletion of abiotic resources fossil fuels (ADP)	6,67E-01	1,79E-01	0,00E+00	2,84E-01	-8,57E-02	**1,04E+00**	kg Sb eq
Climate change (GWP)	1,39E+02	2,49E+01	0,00E+00	4,08E+01	-1,35E+01	**1,91E+02**	kg CO2 eq
Ozone layer depletion (ODP)	7,67E-06	4,21E-06	0,00E+00	6,86E-06	-8,38E-07	**1,79E-05**	kg CFK-11 eq
Photochemical Oxidation (POCP)	7,33E-02	1,87E-02	0,00E+00	3,31E-02	-1,82E-02	**1,07E-01**	kg C2H4 eq
Acidification (AP)	4,67E-01	1,31E-01	0,00E+00	2,48E-01	-6,43E-02	**7,81E-01**	kg SO2 eq
Eutrophication (EP)	8,05E-02	2,68E-02	0,00E+00	5,33E-02	-9,76E-03	**1,51E-01**	kg PO4 eq
Human Toxicity (HTP)	3,94E+01	1,06E+01	0,00E+00	1,62E+01	-6,86E+00	**5,94E+01**	kg 1,4-DCB eq
Freshwater Aquatic Ecotoxicity (FAETP)	1,22E+00	2,79E-01	0,00E+00	3,37E-01	2,57E-02	**1,86E+00**	kg 1,4-DCB eq
Marine Aquatic Ecotoxicity (MAETP)	3,06E+03	9,24E+02	0,00E+00	1,22E+03	-1,49E+02	**5,05E+03**	kg 1,4-DCB eq
Terrestrial Ecotoxicity (TETP)	2,61E+00	1,49E-01	0,00E+00	5,05E-02	4,19E-01	**3,23E+00**	kg 1,4-DCB eq
Environmental Cost Indicator [ECI] (weighted sum)	1,39E+01	3,14E+00	0,00E+00	5,19E+00	-1,68E+00	**2,05E+01**	

SET A2	A1 - A3	A4 - A5	B	C	D	Total	Unit
Climate change - Total	1,77E+02	2,52E+01	0,00E+00	4,11E+01	-1,40E+01	**2,29E+02**	kg CO2 eq
Climate change - Fossil sources	1,72E+02	2,52E+01	0,00E+00	4,11E+01	-1,40E+01	**2,25E+02**	kg CO2 eq
Climate change - Biobased sources	4,40E+00	1,47E-02	0,00E+00	-1,83E-02	2,96E-02	**4,43E+00**	kg CO2 eq
Climate change - Land use changes	1,29E-01	8,95E-03	0,00E+00	9,29E-03	-3,04E-03	**1,44E-01**	kg CO2 eq
Ozone layer depletion	1,03E-05	5,24E-06	0,00E+00	8,57E-06	-9,19E-07	**2,32E-05**	kg CFK11-eq
Acidification	6,00E-01	1,77E-01	0,00E+00	3,41E-01	-8,29E-02	**1,04E+00**	Mol H+eq
Eutrophication of freshwater	7,62E-03	3,00E-04	0,00E+00	4,20E-04	-4,76E-04	**7,86E-03**	kg PO4-eq
Eutrophication of seawater	1,58E-01	6,71E-02	0,00E+00	1,39E-01	-2,19E-02	**3,41E-01**	kg N-eq
Eutrophication of land	1,82E+00	7,38E-01	0,00E+00	1,52E+00	-2,56E-01	**3,82E+00**	Mol N-eq
Smog formation	5,19E-01	2,09E-01	0,00E+00	4,23E-01	-9,05E-02	**1,06E+00**	kg NMVOC-eq
Depletion of abiotic resources minerals and metals	1,15E-03	4,47E-04	0,00E+00	5,00E-04	-4,60E-04	**1,63E-03**	kg Sb-eq
Depletion of abiotic resources fossil fuels	1,46E+03	3,69E+02	0,00E+00	5,90E+02	-1,35E+02	**2,28E+03**	MJ
Water use	7,71E+01	2,09E+00	0,00E+00	1,77E+00	-1,38E+02	**-5,71E+01**	m3 water eq
Particulate matter emissions	7,52E-06	3,53E-06	0,00E+00	7,71E-06	-1,36E-06	**1,74E-05**	ziektegevallen
Ionising radiation	5,24E+00	1,55E+00	0,00E+00	2,45E+00	-2,45E-01	**8,99E+00**	kBq U235-eq
Freshwater Aquatic Ecotoxicity	4,09E+03	3,24E+02	0,00E+00	4,86E+02	-3,66E+02	**4,53E+03**	CTUe
Human toxicity, carcinogenic	4,47E-07	3,04E-08	0,00E+00	1,53E-08	1,33E-08	**5,06E-07**	CTUh
Human toxicity, non-carcinogenic	1,27E-05	8,86E-07	0,00E+00	4,75E-07	1,67E-06	**1,57E-05**	CTUh
Land use-related impact/soil quality	1,20E+03	2,36E+02	0,00E+00	2,88E+02	-1,54E+02	**1,57E+03**	Pt
MKI (gewogen gesommeerd)	3,09E+01	6,10E+00	0,00E+00	1,12E+01	-3,24E+00	**4,49E+01**	

MKI		Set A1		Set A2
A. Production Stage	€	13,84	€	30,85
A. Construction Stage	€	3,14	€	6,11
B. Use Stage	€	-	€	-
C. End-of-Life Stage	€	5,21	€	11,17
D. Beyon Life Stage	€	-1,68	€	-3,24
	€	**20,52**	**€**	**44,90**

VBI Kanaalplaatvloer 150 Groen Cat. 1 m2 --> m3 d 0,15 m

SET A1	A1 - A3	A4 - A5	B	C	D	Total	Unit
Depletion of abiotic resources minerals and metals (ADP)	8,87E-04	2,99E-04	0,00E+00	2,87E-04	-3,19E-04	**1,15E-03**	kg Sb eq
Depletion of abiotic resources fossil fuels (ADP)	7,40E-01	1,43E-01	0,00E+00	1,09E-01	-9,40E-02	**8,97E-01**	kg Sb eq
Climate change (GWP)	1,99E+02	2,12E+01	0,00E+00	1,49E+01	-1,47E+01	**2,21E+02**	kg CO2 eq
Ozone layer depletion (ODP)	8,00E-06	3,35E-06	0,00E+00	2,49E-06	-8,40E-07	**1,30E-05**	kg CFK-11 eq
Photochemical Oxidation (POCP)	5,12E-02	1,23E-02	0,00E+00	9,60E-03	-2,33E-02	**4,97E-02**	kg C2H4 eq
Acidification (AP)	4,25E-01	6,45E-02	0,00E+00	7,13E-02	-6,43E-02	**4,97E-01**	kg SO2 eq
Eutrophication (EP)	1,05E-01	1,20E-02	0,00E+00	1,47E-02	-9,33E-03	**1,22E-01**	kg PO4 eq
Human Toxicity (HTP)	2,53E+01	8,33E+00	0,00E+00	5,75E+00	-8,20E+00	**3,11E+01**	kg 1,4-DCB eq
Freshwater Aquatic Ecotoxicity (FAETP)	1,67E+00	2,17E-01	0,00E+00	1,52E-01	2,37E-02	**2,07E+00**	kg 1,4-DCB eq
Marine Aquatic Ecotoxicity (MAETP)	2,32E+03	8,40E+02	0,00E+00	5,47E+02	-1,25E+02	**3,58E+03**	kg 1,4-DCB eq
Terrestrial Ecotoxicity (TETP)	1,34E+00	3,10E-02	0,00E+00	2,45E-02	4,43E-01	**1,84E+00**	kg 1,4-DCB eq
Environmental Cost Indicator [ECI] (weighted sum)	1,55E+01	2,31E+00	0,00E+00	1,78E+00	-1,87E+00	**1,77E+01**	

SET A2	A1 - A3	A4 - A5	B	C	D	Total	Unit
Climate change - Total	1,99E+02	2,26E+01	0,00E+00	1,51E+01	-1,54E+01	**2,21E+02**	kg CO2 eq
Climate change - Fossil sources	2,01E+02	2,13E+01	0,00E+00	1,51E+01	-1,55E+01	**2,22E+02**	kg CO2 eq
Climate change - Biobased sources	-2,06E+00	1,23E+00	0,00E+00	2,04E-02	6,43E-02	**-7,49E-01**	kg CO2 eq
Climate change - Land use changes	1,07E-01	7,80E-03	0,00E+00	4,63E-03	-1,93E-04	**1,19E-01**	kg CO2 eq
Ozone layer depletion	8,73E-06	4,19E-06	0,00E+00	3,10E-06	-8,53E-07	**1,52E-05**	kg CFK11-eq
Acidification	5,80E-01	8,40E-02	0,00E+00	9,60E-02	-8,13E-02	**6,79E-01**	Mol H+eq
Eutrophication of freshwater	9,33E-03	3,34E-04	0,00E+00	1,96E-04	-5,57E-04	**9,31E-03**	kg PO4-eq
Eutrophication of seawater	1,89E-01	2,45E-02	0,00E+00	3,60E-02	-1,98E-02	**2,29E-01**	kg N-eq
Eutrophication of land	2,23E+00	2,75E-01	0,00E+00	3,97E-01	-2,32E-01	**2,67E+00**	Mol N-eq
Smog formation	5,31E-01	8,73E-02	0,00E+00	1,11E-01	-9,47E-02	**6,35E-01**	kg NMVOC-eq
Depletion of abiotic resources minerals and metals	8,80E-04	2,99E-04	0,00E+00	2,87E-04	-3,19E-04	**1,15E-03**	kg Sb-eq
Depletion of abiotic resources fossil fuels	1,29E+03	2,95E+02	0,00E+00	2,22E+02	-1,42E+02	**1,67E+03**	MJ
Water use	1,53E+01	5,45E+00	0,00E+00	8,80E-01	-9,13E+01	**-6,97E+01**	m3 water eq
Particulate matter emissions	4,62E-06	1,93E-06	0,00E+00	1,77E-06	-1,32E-06	**7,00E-06**	ziektegevallen
Ionising radiation	4,52E+00	1,25E+00	0,00E+00	9,00E-01	-1,55E-01	**6,51E+00**	kBq U235-eq
Freshwater Aquatic Ecotoxicity	1,71E+03	3,20E+02	0,00E+00	1,89E+02	-4,45E+02	**1,78E+03**	CTUe
Human toxicity, carcinogenic	1,85E-07	6,58E-09	0,00E+00	5,89E-09	-4,80E-09	**1,93E-07**	CTUh
Human toxicity, non-carcinogenic	4,53E-06	2,55E-07	0,00E+00	1,91E-07	1,72E-06	**6,70E-06**	CTUh
Land use-related impact/soil quality	2,40E+03	3,05E+02	0,00E+00	1,56E+02	-1,67E+02	**2,69E+03**	Pt
Environmental Cost Indicator [ECI] (weighted sum)	2,99E+01	4,30E+00	0,00E+00	3,35E+00	-3,15E+00	**3,44E+01**	

MKI		**Set A1**		**Set A2**
A. Production Stage	€	15,46	€	29,95
A. Construction Stage	€	2,31	€	4,30
B. Use Stage	€	-	€	-
C. End-of-Life Stage	€	1,78	€	3,35
D. Beyon Life Stage	€	-1,87	€	-3,15
	€	**17,69**	**€**	**34,45**

VBI Kanaalplaatvloer 200 Groen Cat. 1 m2

SET A1	A1 - A3	A4 - A5	B	C	D	Total	Unit
Depletion of abiotic resources minerals and metals (ADP)	1,25E-04	5,19E-05	0,00E+00	4,85E-05	-5,30E-05	1,72E-04	kg Sb eq
Depletion of abiotic resources fossil fuels (ADP)	1,17E-01	2,41E-02	0,00E+00	1,78E-02	-1,52E-02	1,44E-01	kg Sb eq
Climate change (GWP)	3,31E+01	3,62E+00	0,00E+00	2,44E+00	-2,37E+00	3,68E+01	kg CO2 eq
Ozone layer depletion (ODP)	1,20E-06	5,64E-07	0,00E+00	4,05E-07	-1,37E-07	2,03E-06	kg CFK-11 eq
Photochemical Oxidation (POCP)	1,23E-02	2,04E-03	0,00E+00	1,53E-03	-3,71E-03	1,22E-02	kg C2H4 eq
Acidification (AP)	5,92E-02	1,06E-02	0,00E+00	1,14E-02	-1,04E-02	7,08E-02	kg SO2 eq
Eutrophication (EP)	1,54E-02	1,94E-03	0,00E+00	2,33E-03	-1,52E-03	1,82E-02	kg PO4 eq
Human Toxicity (HTP)	4,01E+00	1,40E+00	0,00E+00	9,41E-01	-1,32E+00	5,03E+00	kg 1,4-DCB eq
Freshwater Aquatic Ecotoxicity (FAETP)	2,49E-01	3,70E-02	0,00E+00	2,53E-02	3,36E-03	3,15E-01	kg 1,4-DCB eq
Marine Aquatic Ecotoxicity (MAETP)	3,67E+02	1,43E+02	0,00E+00	9,12E+01	-2,12E+01	5,80E+02	kg 1,4-DCB eq
Terrestrial Ecotoxicity (TETP)	2,06E-01	5,34E-03	0,00E+00	4,10E-03	6,98E-02	2,85E-01	kg 1,4-DCB eq
Environmental Cost Indicator [ECI] (weighted sum)	2,49E+00	3,91E-01	0,00E+00	2,89E-01	-3,01E-01	2,87E+00	

SET A2	A1 - A3	A4 - A5	B	C	D	Total	Unit
Climate change - Total	3,34E+01	3,84E+00	0,00E+00	2,47E+00	-2,48E+00	3,72E+01	kg CO2 eq
Climate change - Fossil sources	3,36E+01	3,65E+00	0,00E+00	2,46E+00	-2,49E+00	3,72E+01	kg CO2 eq
Climate change - Biobased sources	-2,90E-01	1,90E-01	0,00E+00	3,44E-03	9,91E-03	-8,67E-02	kg CO2 eq
Climate change - Land use changes	1,65E-02	1,38E-03	0,00E+00	7,78E-04	-8,52E-05	1,86E-02	kg CO2 eq
Ozone layer depletion	1,31E-06	7,03E-07	0,00E+00	5,06E-07	-1,40E-07	2,38E-06	kg CFK11-eq
Acidification	8,19E-02	1,37E-02	0,00E+00	1,53E-02	-1,32E-02	9,77E-02	Mol H+eq
Eutrophication of freshwater	8,39E-03	6,71E-05	0,00E+00	3,29E-05	-8,98E-05	8,40E-03	kg PO4-eq
Eutrophication of seawater	2,55E-02	3,86E-03	0,00E+00	5,67E-03	-3,23E-03	3,18E-02	kg N-eq
Eutrophication of land	3,08E-01	4,33E-02	0,00E+00	6,26E-02	-3,78E-02	3,76E-01	Mol N-eq
Smog formation	7,66E-02	1,39E-02	0,00E+00	1,76E-02	-1,53E-02	9,28E-02	kg NMVOC-eq
Depletion of abiotic resources minerals and metals	1,25E-04	5,19E-05	0,00E+00	4,85E-05	-5,30E-05	1,72E-04	kg Sb-eq
Depletion of abiotic resources fossil fuels	2,24E+02	4,98E+01	0,00E+00	3,64E+01	-2,30E+01	2,87E+02	MJ
Water use	2,51E+00	1,01E+00	0,00E+00	1,48E-01	-1,52E+01	-1,15E+01	m3 water eq
Particulate matter emissions	8,41E-07	3,08E-07	0,00E+00	2,75E-07	-2,15E-07	1,21E-06	ziektegevallen
Ionising radiation	9,50E-01	2,10E-01	0,00E+00	1,47E-01	-2,70E-02	1,28E+00	kBq U235-eq
Freshwater Aquatic Ecotoxicity	2,98E+02	5,60E+01	0,00E+00	3,12E+01	-7,11E+01	3,14E+02	CTUe
Human toxicity, carcinogenic	2,87E-08	1,11E-09	0,00E+00	9,73E-10	-7,96E-10	3,00E-08	CTUh
Human toxicity, non-carcinogenic	8,94E-07	4,39E-08	0,00E+00	3,18E-08	2,70E-07	1,24E-06	CTUh
Land use-related impact/soil quality	1,85E+02	5,26E+01	0,00E+00	2,63E+01	-2,68E+01	2,37E+02	Pt
Environmental Cost Indicator [ECI] (weighted sum)	5,02E+00	7,17E-01	0,00E+00	5,38E-01	-5,13E-01	5,76E+00	

MKI	Set A1	Set A2
A. Production Stage	€ 2,32	€ 4,49
A. Construction Stage	€ 0,35	€ 0,65
B. Use Stage	€ -	€ -
C. End-of-Life Stage	€ 0,27	€ 0,50
D. Beyon Life Stage	€ -0,28	€ -0,47
	€ 2,65	**€ 5,17**

VBI Kanaalplaatvloer 260 Groen Cat. 1 m2

SET A1	A1 - A3	A4 - A5	B	C	D	Total	Unit
Depletion of abiotic resources minerals and metals (ADP)	1,80E-04	6,65E-05	0,00E+00	6,08E-05	-6,90E-05	**2,38E-04**	kg Sb eq
Depletion of abiotic resources fossil fuels (ADP)	1,59E-01	3,04E-02	0,00E+00	2,18E-02	-2,37E-02	**1,88E-01**	kg Sb eq
Climate change (GWP)	4,28E+01	4,61E+00	0,00E+00	2,98E+00	-3,73E+00	**4,67E+01**	kg CO2 eq
Ozone layer depletion (ODP)	1,62E-06	7,05E-07	0,00E+00	4,94E-07	-1,99E-07	**2,62E-06**	kg CFK-11 eq
Photochemical Oxidation (POCP)	1,78E-02	2,53E-03	0,00E+00	1,84E-03	-6,23E-03	**1,59E-02**	kg C2H4 eq
Acidification (AP)	7,88E-02	1,30E-02	0,00E+00	1,36E-02	-1,57E-02	**8,97E-02**	kg SO2 eq
Eutrophication (EP)	1,97E-02	2,36E-03	0,00E+00	2,77E-03	-2,21E-03	**2,26E-02**	kg PO4 eq
Human Toxicity (HTP)	5,98E+00	1,76E+00	0,00E+00	1,15E+00	-2,12E+00	**6,77E+00**	kg 1,4-DCB eq
Freshwater Aquatic Ecotoxicity (FAETP)	3,22E-01	4,67E-02	0,00E+00	3,13E-02	9,68E-03	**4,10E-01**	kg 1,4-DCB eq
Marine Aquatic Ecotoxicity (MAETP)	5,48E+02	1,81E+02	0,00E+00	1,13E+02	-2,28E+01	**8,19E+02**	kg 1,4-DCB eq
Terrestrial Ecotoxicity (TETP)	2,99E-01	6,87E-03	0,00E+00	5,09E-03	1,26E-01	**4,37E-01**	kg 1,4-DCB eq
Environmental Cost Indicator [ECI] (weighted sum)	3,31E+00	4,92E-01	0,00E+00	3,51E-01	-4,70E-01	**3,68E+00**	

SET A2	A1 - A3	A4 - A5	B	C	D	Total	Unit
Climate change - Total	4,32E+01	4,85E+00	0,00E+00	3,01E+00	-3,91E+00	**4,72E+01**	kg CO2 eq
Climate change - Fossil sources	4,35E+01	4,64E+00	0,00E+00	3,00E+00	-3,93E+00	**4,72E+01**	kg CO2 eq
Climate change - Biobased sources	-2,82E-01	2,01E-01	0,00E+00	4,28E-03	2,04E-02	**-5,63E-02**	kg CO2 eq
Climate change - Land use changes	2,52E-02	1,81E-03	0,00E+00	9,70E-04	4,43E-04	**2,84E-02**	kg CO2 eq
Ozone layer depletion	1,77E-06	8,79E-07	0,00E+00	6,17E-07	-1,98E-07	**3,07E-06**	kg CFK11-eq
Acidification	1,08E-01	1,68E-02	0,00E+00	1,83E-02	-1,98E-02	**1,23E-01**	Mol H+eq
Eutrophication of freshwater	1,13E-02	8,92E-05	0,00E+00	4,10E-05	-1,41E-04	**1,13E-02**	kg PO4-eq
Eutrophication of seawater	3,25E-02	4,61E-03	0,00E+00	6,71E-03	-4,67E-03	**3,92E-02**	kg N-eq
Eutrophication of land	3,94E-01	5,19E-02	0,00E+00	7,41E-02	-5,46E-02	**4,65E-01**	Mol N-eq
Smog formation	1,02E-01	1,68E-02	0,00E+00	2,09E-02	-2,37E-02	**1,16E-01**	kg NMVOC-eq
Depletion of abiotic resources minerals and metals	1,80E-04	6,65E-05	0,00E+00	6,08E-05	-6,90E-05	**2,38E-04**	kg Sb-eq
Depletion of abiotic resources fossil fuels	3,05E+02	6,27E+01	0,00E+00	4,45E+01	-3,47E+01	**3,78E+02**	MJ
Water use	4,37E+00	1,36E+00	0,00E+00	1,84E-01	-1,98E+01	**-1,39E+01**	m3 water eq
Particulate matter emissions	1,23E-06	3,70E-07	0,00E+00	3,20E-07	-3,18E-07	**1,60E-06**	ziektegevallen
Ionising radiation	1,31E+00	2,64E-01	0,00E+00	1,79E-01	-2,24E-02	**1,73E+00**	kBq U235-eq
Freshwater Aquatic Ecotoxicity	4,23E+02	7,26E+01	0,00E+00	3,85E+01	-1,15E+02	**4,19E+02**	CTUe
Human toxicity, carcinogenic	4,87E-08	1,42E-09	0,00E+00	1,20E-09	-1,03E-09	**5,03E-08**	CTUh
Human toxicity, non-carcinogenic	1,39E-06	5,59E-08	0,00E+00	3,92E-08	4,92E-07	**1,98E-06**	CTUh
Land use-related impact/soil quality	2,35E+02	6,72E+01	0,00E+00	3,29E+01	-3,34E+01	**3,02E+02**	Pt
Environmental Cost Indicator [ECI] (weighted sum)	6,65E+00	8,92E-01	0,00E+00	6,46E-01	-7,60E-01	**7,43E+00**	

MKI	Set A1	Set A2
A. Production Stage	3,313	6,648
A. Construction Stage	0,492	0,892
B. Use Stage	0,000	0,000
C. End-of-Life Stage	0,351	0,646
D. Beyon Life Stage	-0,470	-0,760
	€ 3,69	**€ 7,43**

VBI Kanaalplaatvloer 320 Groen Cat. 1 m2

SET A1	A1 - A3	A4 - A5	B	C	D	Total	Unit
Depletion of abiotic resources minerals and metals (ADP)	2,30E-04	7,54E-05	0,00E+00	6,79E-05	-7,94E-05	**2,94E-04**	kg Sb eq
Depletion of abiotic resources fossil fuels (ADP)	2,10E-01	3,43E-02	0,00E+00	2,41E-02	-3,10E-02	**2,37E-01**	kg Sb eq
Climate change (GWP)	5,71E+01	5,23E+00	0,00E+00	3,29E+00	-4,89E+00	**6,07E+01**	kg CO2 eq
Ozone layer depletion (ODP)	2,09E-06	7,91E-07	0,00E+00	5,45E-07	-2,49E-07	**3,18E-06**	kg CFK-11 eq
Photochemical Oxidation (POCP)	2,53E-02	2,83E-03	0,00E+00	2,01E-03	-8,51E-03	**2,16E-02**	kg C2H4 eq
Acidification (AP)	1,01E-01	1,46E-02	0,00E+00	1,49E-02	-2,00E-02	**1,11E-01**	kg SO2 eq
Eutrophication (EP)	2,52E-02	2,64E-03	0,00E+00	3,03E-03	-2,78E-03	**2,81E-02**	kg PO4 eq
Human Toxicity (HTP)	8,03E+00	1,98E+00	0,00E+00	1,27E+00	-2,81E+00	**8,47E+00**	kg 1,4-DCB eq
Freshwater Aquatic Ecotoxicity (FAETP)	3,96E-01	5,27E-02	0,00E+00	3,48E-02	1,62E-02	**5,00E-01**	kg 1,4-DCB eq
Marine Aquatic Ecotoxicity (MAETP)	7,40E+02	2,04E+02	0,00E+00	1,26E+02	-2,17E+01	**1,05E+03**	kg 1,4-DCB eq
Terrestrial Ecotoxicity (TETP)	3,92E-01	7,85E-03	0,00E+00	5,66E-03	1,77E-01	**5,83E-01**	kg 1,4-DCB eq
Environmental Cost Indicator [ECI] (weighted sum)	4,40E+00	5,55E-01	0,00E+00	3,88E-01	-6,16E-01	**4,73E+00**	

SET A2	A1 - A3	A4 - A5	B	C	D	Total	Unit
Climate change - Total	5,79E+01	5,48E+00	0,00E+00	3,32E+00	-5,14E+00	**6,16E+01**	kg CO2 eq
Climate change - Fossil sources	5,82E+01	5,27E+00	0,00E+00	3,32E+00	-5,17E+00	**6,16E+01**	kg CO2 eq
Climate change - Biobased sources	-2,69E-01	2,08E-01	0,00E+00	4,77E-03	3,05E-02	**-2,57E-02**	kg CO2 eq
Climate change - Land use changes	3,40E-02	2,08E-03	0,00E+00	1,08E-03	1,03E-03	**3,82E-02**	kg CO2 eq
Ozone layer depletion	2,29E-06	9,85E-07	0,00E+00	6,81E-07	-2,42E-07	**3,71E-06**	kg CFK11-eq
Acidification	1,39E-01	1,88E-02	0,00E+00	2,00E-02	-2,52E-02	**1,53E-01**	Mol H+eq
Eutrophication of freshwater	1,73E-02	1,08E-04	0,00E+00	4,56E-05	-1,85E-04	**1,73E-02**	kg PO4-eq
Eutrophication of seawater	4,06E-02	5,10E-03	0,00E+00	7,32E-03	-5,82E-03	**4,72E-02**	kg N-eq
Eutrophication of land	5,01E-01	5,75E-02	0,00E+00	8,08E-02	-6,79E-02	**5,71E-01**	Mol N-eq
Smog formation	1,33E-01	1,86E-02	0,00E+00	2,28E-02	-3,10E-02	**1,43E-01**	kg NMVOC-eq
Depletion of abiotic resources minerals and metals	2,30E-04	7,54E-05	0,00E+00	6,79E-05	-7,94E-05	**2,94E-04**	kg Sb-eq
Depletion of abiotic resources fossil fuels	4,09E+02	7,07E+01	0,00E+00	4,92E+01	-4,43E+01	**4,85E+02**	MJ
Water use	4,35E+00	1,60E+00	0,00E+00	2,05E-01	-2,28E+01	**-1,66E+01**	m3 water eq
Particulate matter emissions	1,69E-06	4,09E-07	0,00E+00	3,47E-07	-4,02E-07	**2,04E-06**	ziektegevallen
Ionising radiation	1,80E+00	2,97E-01	0,00E+00	1,98E-01	-1,36E-02	**2,28E+00**	kBq U235-eq
Freshwater Aquatic Ecotoxicity	5,69E+02	8,31E+01	0,00E+00	4,27E+01	-1,54E+02	**5,41E+02**	CTUe
Human toxicity, carcinogenic	6,76E-08	1,61E-09	0,00E+00	1,33E-09	-1,17E-09	**6,94E-08**	CTUh
Human toxicity, non-carcinogenic	1,96E-06	6,35E-08	0,00E+00	4,36E-08	7,00E-07	**2,77E-06**	CTUh
Land use-related impact/soil quality	2,28E+02	7,60E+01	0,00E+00	3,68E+01	-3,82E+01	**3,03E+02**	Pt
Environmental Cost Indicator [ECI] (weighted sum)	8,91E+00	1,00E+00	0,00E+00	7,09E-01	-9,61E-01	**9,66E+00**	

MKI	Set A1	Set A2
A. Production Stage	4,404	8,915
A. Construction Stage	0,555	1,003
B. Use Stage	0,000	0,000
C. End-of-Life Stage	0,388	0,709
D. Beyon Life Stage	-0,616	-0,961
	4,731	**9,666**

VBI Kanaalplaatvloer 400 Groen Cat. 1 m2

SET A1	A1 - A3	A4 - A5	B	C	D	Total	Unit
Depletion of abiotic resources minerals and metals (ADP)	2,76E-04	8,72E-05	0,00E+00	7,73E-05	-9,12E-05	**3,49E-04**	kg Sb eq
Depletion of abiotic resources fossil fuels (ADP)	2,61E-01	4,00E-02	0,00E+00	2,76E-02	-3,84E-02	**2,90E-01**	kg Sb eq
Climate change (GWP)	7,27E+01	6,12E+00	0,00E+00	3,77E+00	-6,07E+00	**7,65E+01**	kg CO2 eq
Ozone layer depletion (ODP)	2,50E-06	9,17E-07	0,00E+00	6,26E-07	-3,01E-07	**3,74E-06**	kg CFK-11 eq
Photochemical Oxidation (POCP)	3,36E-02	3,31E-03	0,00E+00	2,32E-03	-1,08E-02	**2,84E-02**	kg C2H4 eq
Acidification (AP)	1,21E-01	1,72E-02	0,00E+00	1,72E-02	-2,45E-02	**1,31E-01**	kg SO2 eq
Eutrophication (EP)	3,07E-02	3,13E-03	0,00E+00	3,50E-03	-3,37E-03	**3,40E-02**	kg PO4 eq
Human Toxicity (HTP)	9,98E+00	2,29E+00	0,00E+00	1,46E+00	-3,51E+00	**1,02E+01**	kg 1,4-DCB eq
Freshwater Aquatic Ecotoxicity (FAETP)	4,65E-01	6,08E-02	0,00E+00	3,98E-02	2,24E-02	**5,88E-01**	kg 1,4-DCB eq
Marine Aquatic Ecotoxicity (MAETP)	9,25E+02	2,36E+02	0,00E+00	1,43E+02	-2,14E+01	**1,28E+03**	kg 1,4-DCB eq
Terrestrial Ecotoxicity (TETP)	4,83E-01	9,16E-03	0,00E+00	6,45E-03	2,29E-01	**7,28E-01**	kg 1,4-DCB eq
Environmental Cost Indicator [ECI] (weighted sum)	5,54E+00	6,49E-01	0,00E+00	4,45E-01	-7,64E-01	**5,87E+00**	

SET A2	A1 - A3	A4 - A5	B	C	D	Total	Unit
Climate change - Total	7,39E+01	6,39E+00	0,00E+00	3,81E+00	-6,39E+00	**7,77E+01**	kg CO2 eq
Climate change - Fossil sources	7,41E+01	6,17E+00	0,00E+00	3,80E+00	-6,43E+00	**7,76E+01**	kg CO2 eq
Climate change - Biobased sources	-2,52E-01	2,18E-01	0,00E+00	5,43E-03	4,03E-02	**1,17E-02**	kg CO2 eq
Climate change - Land use changes	4,27E-02	2,45E-03	0,00E+00	1,23E-03	1,58E-03	**4,80E-02**	kg CO2 eq
Ozone layer depletion	2,72E-06	1,14E-06	0,00E+00	7,81E-07	-2,89E-07	**4,35E-06**	kg CFK11-eq
Acidification	1,67E-01	2,22E-02	0,00E+00	2,31E-02	-3,08E-02	**1,82E-01**	Mol H+eq
Eutrophication of freshwater	2,49E-02	1,32E-04	0,00E+00	5,20E-05	-2,29E-04	**2,49E-02**	kg PO4-eq
Eutrophication of seawater	4,77E-02	6,10E-03	0,00E+00	8,46E-03	-7,02E-03	**5,52E-02**	kg N-eq
Eutrophication of land	5,98E-01	6,88E-02	0,00E+00	9,34E-02	-8,19E-02	**6,78E-01**	Mol N-eq
Smog formation	1,61E-01	2,21E-02	0,00E+00	2,63E-02	-3,84E-02	**1,71E-01**	kg NMVOC-eq
Depletion of abiotic resources minerals and metals	2,76E-04	8,72E-05	0,00E+00	7,73E-05	-9,12E-05	**3,49E-04**	kg Sb-eq
Depletion of abiotic resources fossil fuels	5,14E+02	8,22E+01	0,00E+00	5,64E+01	-5,42E+01	**5,98E+02**	MJ
Water use	5,52E+00	1,92E+00	0,00E+00	2,34E-01	-2,62E+01	**-1,85E+01**	m3 water eq
Particulate matter emissions	2,16E-06	4,81E-07	0,00E+00	4,03E-07	-4,89E-07	**2,56E-06**	ziektegevallen
Ionising radiation	2,36E+00	3,44E-01	0,00E+00	2,27E-01	-6,41E-03	**2,92E+00**	kBq U235-eq
Freshwater Aquatic Ecotoxicity	7,24E+02	9,78E+01	0,00E+00	4,88E+01	-1,93E+02	**6,78E+02**	CTUe
Human toxicity, carcinogenic	8,61E-08	1,88E-09	0,00E+00	1,52E-09	-1,34E-09	**8,82E-08**	CTUh
Human toxicity, non-carcinogenic	2,58E-06	7,40E-08	0,00E+00	4,98E-08	9,04E-07	**3,61E-06**	CTUh
Land use-related impact/soil quality	2,03E+02	8,77E+01	0,00E+00	4,19E+01	-4,33E+01	**2,89E+02**	Pt
Environmental Cost Indicator [ECI] (weighted sum)	1,13E+01	1,17E+00	0,00E+00	8,16E-01	-1,17E+00	**1,21E+01**	

MKI	Set A1	Set A2
A. Production Stage	5,536	11,336
A. Construction Stage	0,649	1,174
B. Use Stage	0,000	0,000
C. End-of-Life Stage	0,445	0,816
D. Beyon Life Stage	-0,764	-1,169
	5,866	**12,157**

VBI Kanaalplaatvloer 500 Groen Cat. 1 m2

SET A1	A1 - A3	A4 - A5	B	C	D	Total	Unit
Depletion of abiotic resources minerals and metals (ADP)	3,41E-04	1,07E-04	0,00E+00	9,67E-05	-1,22E-04	**4,23E-04**	kg Sb eq
Depletion of abiotic resources fossil fuels (ADP)	3,42E-01	4,93E-02	0,00E+00	3,49E-02	-4,69E-02	**3,79E-01**	kg Sb eq
Climate change (GWP)	9,95E+01	7,50E+00	0,00E+00	4,78E+00	-7,40E+00	**1,04E+02**	kg CO2 eq
Ozone layer depletion (ODP)	3,21E-06	1,14E-06	0,00E+00	7,93E-07	-3,78E-07	**4,77E-06**	kg CFK-11 eq
Photochemical Oxidation (POCP)	4,43E-02	4,12E-03	0,00E+00	2,96E-03	-1,28E-02	**3,86E-02**	kg C2H4 eq
Acidification (AP)	1,58E-01	2,14E-02	0,00E+00	2,20E-02	-3,03E-02	**1,71E-01**	kg SO2 eq
Eutrophication (EP)	4,10E-02	3,90E-03	0,00E+00	4,48E-03	-4,21E-03	**4,52E-02**	kg PO4 eq
Human Toxicity (HTP)	1,24E+01	2,84E+00	0,00E+00	1,84E+00	-4,25E+00	**1,28E+01**	kg 1,4-DCB eq
Freshwater Aquatic Ecotoxicity (FAETP)	5,43E-01	7,51E-02	0,00E+00	5,00E-02	2,40E-02	**6,92E-01**	kg 1,4-DCB eq
Marine Aquatic Ecotoxicity (MAETP)	1,15E+03	2,91E+02	0,00E+00	1,80E+02	-3,40E+01	**1,59E+03**	kg 1,4-DCB eq
Terrestrial Ecotoxicity (TETP)	5,77E-01	1,12E-02	0,00E+00	8,10E-03	2,66E-01	**8,62E-01**	kg 1,4-DCB eq
Environmental Cost Indicator [ECI] (weighted sum)	7,40E+00	8,00E-01	0,00E+00	5,65E-01	-9,31E-01	**7,83E+00**	

SET A2	A1 - A3	A4 - A5	B	C	D	Total	Unit
Climate change - Total	1,01E+02	7,79E+00	0,00E+00	4,83E+00	-7,78E+00	**1,06E+02**	kg CO2 eq
Climate change - Fossil sources	1,01E+02	7,56E+00	0,00E+00	4,82E+00	-7,83E+00	**1,06E+02**	kg CO2 eq
Climate change - Biobased sources	-2,26E-01	2,27E-01	0,00E+00	6,80E-03	4,58E-02	**5,36E-02**	kg CO2 eq
Climate change - Land use changes	5,30E-02	2,94E-03	0,00E+00	1,54E-03	1,52E-03	**5,90E-02**	kg CO2 eq
Ozone layer depletion	3,50E-06	1,42E-06	0,00E+00	9,90E-07	-3,68E-07	**5,54E-06**	kg CFK11-eq
Acidification	2,21E-01	2,76E-02	0,00E+00	2,96E-02	-3,82E-02	**2,40E-01**	Mol H+eq
Eutrophication of freshwater	3,53E-02	1,63E-04	0,00E+00	6,52E-05	-2,79E-04	**3,52E-02**	kg PO4-eq
Eutrophication of seawater	6,35E-02	7,67E-03	0,00E+00	1,09E-02	-8,83E-03	**7,32E-02**	kg N-eq
Eutrophication of land	8,08E-01	8,64E-02	0,00E+00	1,20E-01	-1,03E-01	**9,11E-01**	Mol N-eq
Smog formation	2,13E-01	2,77E-02	0,00E+00	3,39E-02	-4,69E-02	**2,28E-01**	kg NMVOC-eq
Depletion of abiotic resources minerals and metals	3,41E-04	1,07E-04	0,00E+00	9,67E-05	-1,22E-04	**4,23E-04**	kg Sb-eq
Depletion of abiotic resources fossil fuels	6,80E+02	1,02E+02	0,00E+00	7,14E+01	-6,73E+01	**7,86E+02**	MJ
Water use	6,27E+00	2,24E+00	0,00E+00	2,94E-01	-3,51E+01	**-2,63E+01**	m3 water eq
Particulate matter emissions	2,79E-06	6,08E-07	0,00E+00	5,22E-07	-6,09E-07	**3,31E-06**	ziektegevallen
Ionising radiation	3,16E+00	4,27E-01	0,00E+00	2,87E-01	-2,30E-02	**3,85E+00**	kBq U235-eq
Freshwater Aquatic Ecotoxicity	9,26E+02	1,18E+02	0,00E+00	6,15E+01	-2,32E+02	**8,74E+02**	CTUe
Human toxicity, carcinogenic	1,02E-07	2,30E-09	0,00E+00	1,91E-09	-1,79E-09	**1,04E-07**	CTUh
Human toxicity, non-carcinogenic	3,26E-06	9,11E-08	0,00E+00	6,27E-08	1,05E-06	**4,46E-06**	CTUh
Land use-related impact/soil quality	2,62E+02	1,08E+02	0,00E+00	5,24E+01	-5,43E+01	**3,68E+02**	Pt
Environmental Cost Indicator [ECI] (weighted sum)	1,53E+01	1,45E+00	0,00E+00	1,04E+00	-1,46E+00	**1,63E+01**	

MKI	Set A1	Set A2
A. Production Stage	7,402	15,338
A. Construction Stage	0,800	1,446
B. Use Stage	0,000	0,000
C. End-of-Life Stage	0,565	1,042
D. Beyon Life Stage	-0,931	-1,459
	7,836	**16,367**

Vrijdragende Vloeren, Staalplaatbetonvloer, SBV210	A1	Cat. 3	m2	d =	0,21
A2-Vrijdragende Vloeren, Staalplaatbetonvloer, SBV210	A2	Cat. 3	m2		

SET A1	**A1 - A3**	**A4 - A5**	**B**	**C**	**D**	**Total**	**Unit**
Depletion of abiotic resources minerals and metals (ADP)	4,21E-04	3,06E-05	0,00E+00	1,16E-05	-1,69E-04	**2,95E-04**	kg Sb eq
Depletion of abiotic resources fossil fuels (ADP)	1,75E+00	7,95E-02	0,00E+00	3,39E-02	-6,38E-01	**1,22E+00**	kg Sb eq
Climate change (GWP)	3,45E+02	1,08E+01	0,00E+00	4,51E+00	-1,29E+02	**2,31E+02**	kg CO2 eq
Ozone layer depletion (ODP)	6,86E-06	1,98E-06	0,00E+00	1,24E-06	0,00E+00	**1,01E-05**	kg CFK-11 eq
Photochemical Oxidation (POCP)	1,56E-01	6,33E-03	0,00E+00	3,66E-03	-6,52E-02	**1,01E-01**	kg C2H4 eq
Acidification (AP)	1,04E+00	4,66E-02	0,00E+00	2,33E-02	-2,40E-01	**8,73E-01**	kg SO2 eq
Eutrophication (EP)	1,14E-01	9,33E-03	0,00E+00	5,29E-03	-1,37E-02	**1,15E-01**	kg PO4 eq
Human Toxicity (HTP)	2,05E+01	4,30E+00	0,00E+00	2,03E+00	0,00E+00	**2,68E+01**	kg 1,4-DCB eq
Freshwater Aquatic Ecotoxicity (FAETP)	8,14E-01	1,26E-01	0,00E+00	5,62E-02	-1,65E-01	**8,32E-01**	kg 1,4-DCB eq
Marine Aquatic Ecotoxicity (MAETP)	4,39E+03	4,55E+02	0,00E+00	3,49E+02	0,00E+00	**5,19E+03**	kg 1,4-DCB eq
Terrestrial Ecotoxicity (TETP)	2,46E-01	1,52E-02	0,00E+00	1,72E-02	0,00E+00	**2,79E-01**	kg 1,4-DCB eq
Environmental Cost Indicator [ECI] (weighted sum)	€ 25,33	€ 1,27	€ -	€ 0,60	€ -7,76	**€ 19,44**	

SET A2	**A1 - A3**	**A4 - A5**	**B**	**C**	**D**	**Total**	**Unit**
Climate change - Total	3,17E+02	2,79E+01	0,00E+00	1,67E+01	-1,23E+01	**3,49E+02**	kg CO2 eq
Climate change - Fossil sources	3,16E+02	2,78E+01	0,00E+00	1,67E+01	-1,23E+01	**3,48E+02**	kg CO2 eq
Climate change - Biobased sources	5,24E-01	4,04E-02	0,00E+00	-1,50E-02	5,95E-03	**5,55E-01**	kg CO2 eq
Climate change - Land use changes	6,14E-01	7,14E-02	0,00E+00	4,66E-02	-2,64E-02	**7,06E-01**	kg CO2 eq
Ozone layer depletion	2,82E-06	3,68E-07	0,00E+00	3,04E-07	-1,96E-07	**3,30E-06**	kg CFK11-eq
Acidification	1,33E+00	1,25E-01	0,00E+00	1,00E-01	-6,33E-02	**1,49E+00**	Mol H+eq
Eutrophication of freshwater	2,05E-02	8,05E-04	0,00E+00	2,79E-04	-7,33E-04	**2,08E-02**	kg PO4-eq
Eutrophication of seawater	3,29E-01	4,05E-02	0,00E+00	3,42E-02	-1,67E-02	**3,87E-01**	kg N-eq
Eutrophication of land	3,97E+00	4,59E-01	0,00E+00	3,72E-01	-1,89E-01	**4,61E+00**	Mol N-eq
Smog formation	1,13E+00	1,44E-01	0,00E+00	1,21E-01	-6,90E-02	**1,33E+00**	kg NMVOC-eq
Depletion of abiotic resources minerals and metals	7,81E-04	7,86E-05	0,00E+00	2,03E-04	-4,05E-05	**1,02E-03**	kg Sb-eq
Depletion of abiotic resources fossil fuels	2,40E+03	3,00E+02	0,00E+00	2,37E+02	-1,36E+02	**2,80E+03**	MJ
Water use	8,90E+01	4,15E+00	0,00E+00	1,80E+00	-5,95E+00	**8,91E+01**	m3 water eq
Particulate matter emissions	1,92E-05	2,17E-06	0,00E+00	1,91E-06	-1,32E-06	**2,19E-05**	ziektegevallen
Ionising radiation	5,10E+00	2,71E-01	0,00E+00	1,93E-01	-2,40E-01	**5,32E+00**	kBq U235-eq
Freshwater Aquatic Ecotoxicity	1,91E+03	2,20E+02	0,00E+00	1,64E+02	-6,29E+01	**2,23E+03**	CTUe
Human toxicity, carcinogenic	2,68E-06	9,43E-08	0,00E+00	1,09E-08	-7,52E-08	**2,71E-06**	CTUh
Human toxicity, non-carcinogenic	9,95E-06	5,19E-07	0,00E+00	3,26E-07	-1,56E-07	**1,06E-05**	CTUh
Land use-related impact/soil quality	1,14E+03	2,14E+02	0,00E+00	2,04E+02	-9,76E+01	**1,46E+03**	Pt
Environmental Cost Indicator [ECI] (weighted sum)	€ 58,10	€ 5,33	€ -	€ 3,62	€ -2,60	**€ 64,46**	

MKI	**Set A1**	**Set A2**
A. Production Stage	€ 25,36	€ 58,05
A. Construction Stage	€ 1,27	€ 5,31
B. Use Stage	€ -	€ -
C. End-of-Life Stage	€ 0,60	€ 3,62
D. Beyon Life Stage	€ -7,76	€ -2,60
	€ 19,47	**€ 64,39**

Wapeningsstaal (Reinforcement)	A1	Cat. 3	ton --> kg
A2-Voorspanstaal, wapeningsstaal, per kg	A2	Cat. 3	kg

SET A1	**A1 - A3**	**A4 - A5**	**B**	**C**	**D**	**Total**	**Unit**
Depletion of abiotic resources minerals and metals (ADP)	2,33E-06	1,21E-07	0,00E+00	5,79E-07	1,38E-07	**3,17E-06**	kg Sb eq
Depletion of abiotic resources fossil fuels (ADP)	1,17E-02	4,96E-04	0,00E+00	2,08E-04	-9,68E-04	**1,14E-02**	kg Sb eq
Climate change (GWP)	1,59E+00	6,68E-02	0,00E+00	3,06E-02	-1,59E-01	**1,53E+00**	kg CO2 eq
Ozone layer depletion (ODP)	1,05E-07	6,74E-09	0,00E+00	3,99E-09	-7,28E-09	**1,08E-07**	kg CFK-11 eq
Photochemical Oxidation (POCP)	1,64E-03	6,12E-05	0,00E+00	2,55E-05	-3,72E-04	**1,35E-03**	kg C2H4 eq
Acidification (AP)	6,69E-03	2,76E-04	0,00E+00	2,76E-04	-5,96E-04	**6,65E-03**	kg SO2 eq
Eutrophication (EP)	8,99E-04	4,19E-05	0,00E+00	6,18E-05	-6,03E-05	**9,42E-04**	kg PO4 eq
Human Toxicity (HTP)	8,88E-01	3,11E-02	0,00E+00	2,95E-02	-1,02E-01	**8,47E-01**	kg 1,4-DCB eq
Freshwater Aquatic Ecotoxicity (FAETP)	2,77E-02	9,97E-04	0,00E+00	4,37E-04	1,71E-03	**3,08E-02**	kg 1,4-DCB eq
Marine Aquatic Ecotoxicity (MAETP)	6,14E+01	2,31E+00	0,00E+00	2,15E+00	1,85E+00	**6,77E+01**	kg 1,4-DCB eq
Terrestrial Ecotoxicity (TETP)	6,77E-02	2,06E-03	0,00E+00	9,80E-05	1,16E-02	**8,15E-02**	kg 1,4-DCB eq
Environmental Cost Indicator [ECI] (weighted sum)	2,11E-01	8,20E-03	0,00E+00	6,17E-03	-2,00E-02	**2,05E-01**	

SET A2	**A1 - A3**	**A4 - A5**	**B**	**C**	**D**	**Total**	**Unit**
Climate change - Total	2,06E+00	1,36E-01	0,00E+00	4,21E-02	-1,11E-01	**2,13E+00**	kg CO2 eq
Climate change - Fossil sources	2,05E+00	1,35E-01	0,00E+00	4,25E-02	-1,13E-01	**2,11E+00**	kg CO2 eq
Climate change - Biobased sources	6,09E-03	3,25E-04	0,00E+00	-5,41E-04	2,34E-03	**8,21E-03**	kg CO2 eq
Climate change - Land use changes	1,81E-03	2,03E-04	0,00E+00	8,33E-05	5,95E-05	**2,16E-03**	kg CO2 eq
Ozone layer depletion	2,82E-08	1,98E-09	0,00E+00	7,00E-10	-4,32E-09	**2,66E-08**	kg CFK11-eq
Acidification	8,79E-03	6,06E-04	0,00E+00	4,10E-04	-3,19E-04	**9,49E-03**	Mol H+eq
Eutrophication of freshwater	1,80E-04	9,37E-06	0,00E+00	1,57E-06	1,28E-05	**2,04E-04**	kg PO4-eq
Eutrophication of seawater	1,99E-03	1,60E-04	0,00E+00	1,01E-04	-5,64E-05	**2,19E-03**	kg N-eq
Eutrophication of land	2,01E-02	1,65E-03	0,00E+00	1,14E-03	-1,09E-03	**2,18E-02**	Mol N-eq
Smog formation	8,90E-03	6,64E-04	0,00E+00	3,51E-04	-7,97E-04	**9,12E-03**	kg NMVOC-eq
Depletion of abiotic resources minerals and metals	5,13E-06	4,52E-07	0,00E+00	2,00E-06	4,37E-07	**8,02E-06**	kg Sb-eq
Depletion of abiotic resources fossil fuels	2,30E+01	1,62E+00	0,00E+00	5,89E-01	-9,61E-01	**2,42E+01**	MJ
Water use	1,06E+00	5,58E-02	0,00E+00	7,29E-03	2,49E-02	**1,15E+00**	m3 water eq
Particulate matter emissions	1,85E-07	1,26E-08	0,00E+00	5,98E-09	-1,09E-08	**1,93E-07**	ziektegevallen
Ionising radiation	4,23E-02	2,35E-03	0,00E+00	1,21E-03	2,64E-03	**4,85E-02**	kBq U235-eq
Freshwater Aquatic Ecotoxicity	1,72E+01	1,20E+00	0,00E+00	4,52E-01	1,48E+00	**2,03E+01**	CTUe
Human toxicity, carcinogenic	2,82E-08	1,43E-09	0,00E+00	5,44E-11	1,75E-09	**3,14E-08**	CTUh
Human toxicity, non-carcinogenic	8,44E-08	4,68E-09	0,00E+00	2,32E-09	1,46E-08	**1,06E-07**	CTUh
Land use-related impact/soil quality	5,88E+00	6,83E-01	0,00E+00	9,05E-01	-1,56E-01	**7,31E+00**	Pt
Environmental Cost Indicator [ECI] (weighted sum)	4,31E-01	2,82E-02	0,00E+00	1,03E-02	-1,63E-02	**4,53E-01**	

MKI		**Set A1**		**Set A2**
A. Production Stage	€	0,21	€	0,43
A. Construction Stage	€	0,01	€	0,03
B. Use Stage	€	-	€	-
C. End-of-Life Stage	€	0,01	€	0,01
D. Beyon Life Stage	€	-0,02	€	-0,02
	€	**0,20**	**€**	**0,45**

E

Excel Calculations

This appendix contains the Excel calculations performed for the design of three different slab types: cast in situ concrete slab, hollow core slab, and deep deck composite slab. The calculations cover applied loads, bending moments, shear forces, deflections, and reinforcement requirements for each slab. Table E.1 provides an overview of the content included on each page.

Table E.1: Overview of Excel Calculations for Slabs

Page Number	Content Description
115	Cast in situ concrete slab calculations
116	Hollow core slab calculations
117	Deep deck composite slab calculations

CAST IN-SITU CONCRETE						
				P_q,rep	P_q,rep	
Self-weight	0,15	25	=	3,75		kN/m2
Office			=		2,50	kN/m2
				3,75	2,50	kN/m2

L	=	5400	mm	Span
b	=	1000	mm	1 m width strip
h	=	150	mm	Height of the slab
c	=	20	mm	Concrete cover
d	=	125	mm	
z	=	112,5	mm	Internal lever arm
f_ck	=	20	MPa	Compressive strength of concrete
f_cm	=	28	MPa	EC2 Table 3.1
E_c	=	29,96	GPa	EC2 Table 3.1
γ_c	=	1,5	-	
f_yd	=	435	MPa	
f_yk	=	500	MPa	
γ_s	=	1,15	-	

A_s	=	785,4	mm2/m	
d_r	=	10		Diameter reinforcement
s	=	100		Spacing reinforcement

Forces			
F_c	=	597,33	kN
F_s	=	341,48	kN
F_gov	=	341,48	kN
M_Ed	=	30,07	kNm
M_Rd	=	38,42	kNm
U.C.	=	0,78	-

Deflection			
E_c	=	29961,95105	MPa
I	=	2,81E+08	mm4
δ	=	8,21	mm
δ_max	=	21,60	mm
U.C.	=	0,38	-

Normal Stresses			
σ_top	=	8,02	MPa
σ_bot	=	8,02	MPa

V_Ed	=	22,28	kN
M_Ed	=	30,07	kNm
M_Rd	=	38,42	kNm
q_d,ULS	=	8,25	kN/m2
q_d,SLS	=	6,25	kN/m2

α	=	0,8	-	EC2
x	=	56	mm	

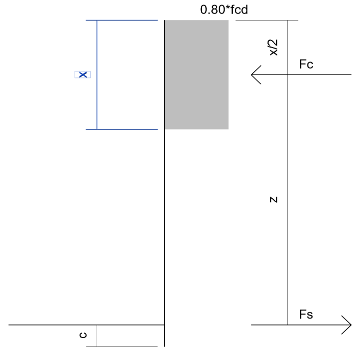
Quantity	V [m3]	V [m3/m2]	ρ [kg/m3]	m [kg/m2]
Concrete	2,025	0,150	2400	360,00
Reinforcement	0,010603	0,000785	7850	6,17

Shear Force				
v_1	=	0,6		EC2 NA 6.2.3
v	=	0,552		EC2 NA 6.2.2
v_min	=	0,443		EC2 NA 6.2.2
k	=	2,00		EC2 6.2.2
k_1	=	0,15		EC2 NA 6.2.2
ρ_l	=	0,006283185	-	
A_sl	=	785	mm2	
σ_cp	=	0,00	MPa	
C_Rd,c	=	0,12	-	EC2 NA 6.2.2
if V_Ed =< V_Rd no calc. Shear reinf. Needed				
V_Rd,c	=	55,34	kN	EC2 6.2.2
V_Ed	=	22,28 kN		
U.C.	=	0,40	-	

U.C.			
Slab	#1	#2	#3
BM	0,783	0,817	0,803
SF	0,403	0,146	0,460
Defl.	0,380	0,288	0,528

LC	f_ck	Unit
LC1	20	MPa
LC2	15,40	MPa
LC3	11,86	MPa

L	5,4	m
b	2,5	m
Area	13,5	m2



δ	=	8,212	mm
δ_max	=	21,600	mm
U.C.	=	0,380	-

M_Ed	=	30,071	kNm
M_Rd	=	38,416	kNm
U.C.	=	0,783	-

V_Ed	=	22,275	kN
V_Rd,c	=	55,340	kN
U.C.	=	0,403	-

HOLLOW CORE SLAB (VBI)				
		P_q,rep	P_q,rep	
VBI150	=	2,68		kN/m2
Office	=		2,50	kN/m2
		2,68	2,50	kN/m2

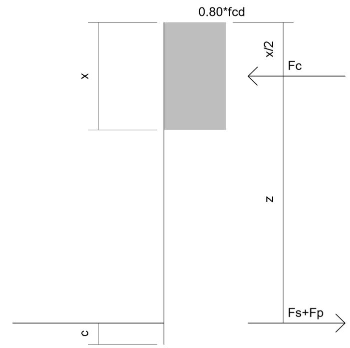
L	=	5400	mm
V_Ed	=	18,81	kN
M_Ed	=	25,39	kNm
q_d,ULS	=	6,97	kN/m2
q_d,SLS	=	5,18	kN/m2

U.C.			
Slab	#1	#2	#3
BM	0,783	0,817	0,803
SF	0,403	0,146	0,460
Defl.	0,380	0,288	0,528

Prestressed Tendons								
A_tendon	=	19,63	mm2	d_t	=	5	mm	
A_p,bottom	=	196,35	mm2	n_bottom	=	10	-	
A_p,top	=	39,27	mm2	n_top	=	2	-	
				σ_pe	=	1100	MPa	
F_p,bottom	=	196,35	kN	γ_p	=	1,1	-	material factor prestressed steel
F_p,top	=	39,27	kN	A_c	=	126076	mm2	
F_p,net	=	157,08	kN					

Reinforcement								
A_s	=	261,80	mm2	d_r	=	10	mm	diameter reinforcement
				f_yk		500	MPa	
F_s	=	113,83	kN	γ_s		1,15	-	material factor steel
				s	=	300	mm	spacing

LC	f_ck	Unit
LC1	20	MPa
LC2	15,40	MPa
LC3	11,86	MPa



Total			
F_s,total	=	270,91	kN

Forces			
F_c	=	731,14	kN
F_s,total	=	270,91	kN
F_gov	=	270,91	kN

Bending Moment Resistance			
M_Rd,p, only	=	18,02	kNm
M_Rd,s, only	=	13,06	kNm
M_Rd	=	31,09	kNm
U.C.	=	0,82	-

α	=	0,8	EC2	check
b	=	1200	mm	
x	=	57,12	mm	correct
d	=	127,5	mm	addd formula
f_ck	=	20	MPa	C20/25
f_cm	=	28	MPa	EC2 Table 3.1
E_c	=	29,96195	GPa	EC2 Table 3.1
z	=	114,75	mm	
γ_c	=	1,5	-	
h	=	150	mm	
c	=	20	mm	

L	5,4	m
b	2,5	m
Area	13,5	m2

Quantity	V [m3]	V [m3/m2]	ρ [kg/m3]	m [kg/m2]
Concrete	1,42	0,105	2400	252,15
Reinforcement	0,00295	0,000218	7850	1,71
Tendons	0,00265	0,000196	7850	1,54
Steel Plate	0,00405	0,000300	7851	2,36

Shear Force					
v_1	=	0,6		EC2 NA 6.2.3	if calc. shear reinf. is needed
v	=	0,552		EC2 NA 6.2.2	if no calc. shear reinf. is needed
v_min	=	0,442718872		EC2 NA 6.2.2	
k	=	2,00		EC2 6.2.2	
k_1	=	0,15		EC2 NA 6.2.2	
ρ_l	=	0,003251104	-		
A_sl	=	497,42	mm2		
σ_cp	=	2,67	MPa		
C_Rd,c	=	0,12	-	EC2 NA 6.2.2	
if V_Ed =< V_Rd,c		no calc. Shear reinf. Needed			
V_Rd,c	=	128,94	kN	EC2 6.2.2	
V_Ed	=	18,81	kN		
U.C.	=	0,15	-		

Deflection			
E	=	29961,95105	MPa
I	=	3,08E+08	mm4
δ	=	6,21	mm
δ_max	=	21,6	mm
U.C.	=	0,29	-

Steel Plate Bonding			
A_plate	=	300	mm2
F_ypd	=	275	MPa
z_plate	=	123,44	mm
b_p	=	90	mm
t_p	=	4	mm
M_Rd,plate	=	10,184	kNm
M_Ed	=	25,39107	kNm
M_Rd,int	=	31,558	kNm
U.C.	=	0,804589	-

Normal Stresses			
σ_top	=	6,18	MPa
σ_bot	=	6,18	MPa

ComFlor210 (Dutch Engineering)				
270		P_q,rep	P_q,rep	
Self-weight	=	2,67		kN/m2
Office	=		2,50	kN/m2
		2,67	2,50	kN/m2

V_Ed	=	18,78	kN	
U.C.	=	0,70	-	
M_Rd	=	36,45	kNm	
M_Ed	=	25,347	kNm	
q_d,ULS	=	6,954	kN/m2	
q_d,SLS	=	5,170	kN/m2	

U.C.			
Slab	#1	#2	#3
BM	0,783	0,817	0,803
SF	0,403	0,146	0,460
Defl.	0,380	0,288	0,528

L	=	5400	mm	Span
b	=	1000	mm	1 m width strip
h	=	270	mm	Height of the slab
c	=	20	mm	Concrete cover
d	=	247	mm	
z	=	222,3	mm	Internal lever arm
f_ck	=	20	MPa	Compressive strength of concrete
f_cm	=	28	MPa	EC2 Table 3.1
E_c	=	29,96	GPa	EC2 Table 3.1
γ_c	=	1,5	-	
f_yd	=	435	MPa	
f_yk	=	500	MPa	
γ_s	=	1,15	-	

L	5,4	m
b	2,5	m
Area	13,5	m2

LC	f_ck	Unit
LC1	20	MPa
LC2	15,40	MPa
LC3	11,86	MPa

α	=	0,85	-	EC4
x	=	110,656	mm	

Quantity	V [m3]	V [m3/m2]	ρ [kg/m3]	m [kg/m2]
Concrete	1,36	0,101	2400	242,40
Reinforcement	0,0006	0,0000471	7850	0,37
Steel plate	0,0224	0,0016561	7850	13,0
SBV210		0,113		267

Steel beam (IPE270)				
f_y	=	355,00	Mpa	Yield Strength Steel Beam
h_a	=	270,00	mm	beam height
b_a	=	135,00	mm	flange width
t_w	=	6,60	mm	web thickness
t_f	=	10,20	mm	flange thickness
h_w	=	249,60	mm	beam web height
r	=	15,00	mm	root radius
A_a	=	4401,36	mm2	Area of steel beam
Ia	=	5,50E+07	mm4	
Ia,plastic	=	5,50E+07	mm4	
Wa	=	4,61E+05	mm3	
A	=	4595	mm2	
A_v	=	2214,32	mm2	

Beam classification		
cf	64,20	Flange
cf/tf	6,29	
ε	0,81	
Class of flange	1	Class, flange
cw	229,20	Web
cw/tw	34,73	
Class of web	1	Class, web
Beam Class	1	Class of beam

A_s	=	47	mm2	
d_r	=	6		Diameter reinforcement
s	=	600		Spacing reinforcement

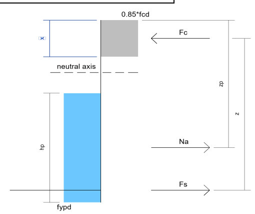
Forces			
F_c	=	1254,10	kN
F_s	=	20,49	kN
F_gov	=	20,49	kN

Shear Force					
v_1	=	0,6		EC2 NA 6.2.3	if calc. shear reinf. is needed
v	=	0,552		EC2 NA 6.2.2	if no calc. shear reinf. is needed
v_min	=	0,410		EC2 NA 6.2.2	
k	=	1,90		EC2 6.2.2	
k_1	=	0,15		EC2 NA 6.2.2	
ρ_l	=	0,000190785	-		
A_sl	=	47	mm2		
σ_cp	=	0,00	MPa		
C_Rd,c	=	0,12	-	EC2 NA 6.2.2	
V_Ed =< V_Rd,c		no calc. Shear reinf. Needed			
V_Rd,c	=	40,84	kN	EC2 6.2.2	
V_Ed	=	18,78	-		
U.C.	=	0,46	-		

Deflection			
h	=	270	mm
h_p	=	210	mm
h_c	=	60	mm
L	=	5400	mm
b_eff	=	1000	mm
f_ck	=	20	MPa
f_cm	=	28	MPa
E_c	=	29,96	GPa
q_d,SLS	=	5,170	kN/m2
q_d,ULS	=	6,954	kN/m2
A_p	=	1627	mm2/m
A_c	=	60000	mm2/m
A_c,tr	=	8560,557444	mm2/m
EI_0	=	2,11E+12	Nmm2
EI_eff	=	5,02E+12	Nmm2
e_T	=	46,082	mm
a_p	=	84,618	mm
a_c	=	16,082	mm
δ	=	11,41	mm
δ_max	=	21,60	mm
U.C.	=	0,53	-

Vertical Shear (EC3-1-1 Design Verification)				
V_Ed	=	18,78	kN	
V_pl,Rd	=	453,846	kN	
U.C.	=	0,04	-	
V_Ed =< 0,5 V_pl,Rd		Yes		No reduction on M_N,y,Rd
V_Ed > 0,5 V_pl,Rd		No		Reduction on M_N,y,Rd

n	=	7	-					
E_s	=	210000	MPa		I_p	=	7,46E+06	mm4
E_c	=	29962	MPa		I_c	=	18000000	mm4
e_p,plate only	=	70,7	mm	from top of steel plate				
z_p	=	130,7	mm	from top of slab				
z_c	=	30	mm	from top of slab				



Bending Moment Resistance				
x	=	46,082	mm	
z	=	220,959	mm	
c	=	20	mm	
f_yd	=	435	MPa	
f_ypd	=	275	MPa	
f_yk	=	500	MPa	
γ_s	=	1,15	-	
A_s	=	47	mm2	
d_r	=	6		Diameter reinforcement
s	=	600		Spacing reinforcement
M_Ed	=	25,347	kNm	
M_Rd,s	=	4,527	kNm	
M_Rd,p	=	27,033	kNm	
M_Rd,tot	=	31,561	kNm	
U.C.	=	0,803	-	

Normal Stresses			
σ_top	=	6,98	MPa
σ_bot	=	33,89	MPa

F
Corrosion Calculation

This appendix presents the results of corrosion calculations focusing on the effects of carbonation on reinforcement over three life cycles. The calculations, performed using Excel, provide insights into the reduction of effective reinforcement area and its impact on the expected service life of structural components.

D	=	k√t	→	t_cor	=	(c/k)^2	=	27,27	years			
k	=	3,83	-	carbonation coefficient (from lit.)								
c	=	20	mm	concrete cover								
t_1	=	50	years	→	t_cor,pr	=	22,73	years	→	p	=	0,10115 mm
t_2	=	100	years	→	t_cor,pr	=	72,73	years	→	p	=	0,32364 mm
t_3	=	150	years	→	t_cor,pr	=	122,73	years	→	p	=	0,54613 mm
p	=	r_cor * t_cor,pr		corrosion penetration								
r_cor	=	4,44976	μm / year	corrosion rate								
		0,00445	mm / year	corrosion rate								

Slab 1

d_r	=	10	mm
s	=	100	mm
A_s	=	785,40	mm2
z	=	112,5	mm
d_remaining	=	9,798	mm
d_remaining	=	9,353	mm
d_remaining	=	8,908	mm
A_remaining	=	753,943	mm2
A_remaining	=	687,015	mm2
A_remaining	=	623,198	mm2
% Loss	=	4,17%	%
% Loss	=	14,32%	%
% Loss	=	26,03%	%
A_s	=	785,40	mm2
after t_1	:	752,63	mm2
after t_2	:	672,93	mm2
after t_3	:	580,98	mm2

Slab 2

		Reinf.	Top Tend.	Bot. Tend.	
d_r	=	10	5	5	mm
s	=	300	500	100	mm
A_s	=	261,80	39,27	196,35	mm2
z	=	114,75			mm
		Reinf.	Top Tend.	Bot. Tend.	
d	=	10	5	5	
s	=	300	500	100	
d_remaining	=	9,798	4,798	4,798	mm
d_remaining	=	9,353	4,353	4,353	mm
d_remaining	=	8,908	3,908	3,908	mm
A_remaining	=	251,314	36,156	180,782	mm2
A_remaining	=	229,005	29,761	148,803	mm2
A_remaining	=	207,733	23,987	119,934	mm2
% Loss	=	4,17%	8,61%	8,61%	%
% Loss	=	14,32%	31,95%	31,95%	%
% Loss	=	26,03%	63,71%	63,71%	%
A_s	=	261,80	39,27	196,35	mm2
after t_1	:	250,88	35,89	179,44	mm2
after t_2	:	224,31	26,72	133,61	mm2
after t_3	:	193,66	14,25	71,25	mm2

Slab 3

d_r	=	6	mm	
s	=	600	mm	
A_s	=	47,12	mm2	
z	=	220,96	mm	
d_remaining	=	5,798	mm	
d_remaining	=	5,353	mm	
d_remaining	=	4,908	mm	
A_remaining	=	44,000	mm2	
A_remaining	=	37,505	mm2	
A_remaining	=	31,529	mm2	
% Loss	=	7,10%	%	
% Loss	=	25,65%	%	
% Loss	=	49,46%	%	
A_s	=	47,12	mm2	at 0 years
after t_1	:	43,78	mm2	at 50 years
after t_2	:	35,04	mm2	at 100 years
after t_3	:	23,81	mm2	at 150 years

Slab 1			
V_Ed	=	22,275	kN
M_Ed	=	30,071	kNm
M_Rd	=	38,435	kNm
U.C.	=	0,782	-
M_Rd	=	36,832	kNm
U.C.	=	0,816	-
M_Rd	=	32,931	kNm
U.C.	=	0,913	-
M_Rd	=	28,432	kNm
U.C.	=	1,058	-
V_Rd	=	55,340	kN
U.C.	=	0,403	-
V_Rd	=	55,340	kN
U.C.	=	0,403	-
V_Rd	=	N.A.	kN
U.C.	=	N.A.	-
V_Rd	=	N.A.	kN
U.C.	=	N.A.	-

Slab 2			
V_Ed	=	18,808	kN
M_Ed	=	25,391	kNm
M_Rd	=	31,086	kNm
U.C.	=	0,817	-
M_Rd	=	29,134	kNm
U.C.	=	0,872	-
M_Rd	=	25,085	kNm
U.C.	=	1,012	-
M_Rd	=	21,374	kNm
U.C.	=	1,188	-
V_Rd	=	128,936	kN
U.C.	=	0,146	-
V_Rd	=	128,370	kN
U.C.	=	0,147	-
V_Rd	=	125,333	kN
U.C.	=	0,150	-
V_Rd	=	122,255	kN
U.C.	=	0,154	-

Slab 3			
V_Ed	=	18,776	kN
M_Ed	=	25,347	kNm
M_Rd	=	31,563	kNm
U.C.	=	0,803	-
M_Rd	=	31,241	kNm
U.C.	=	0,811	-
M_Rd	=	30,401	kNm
U.C.	=	0,834	-
M_Rd	=	29,322	kNm
U.C.	=	0,864	-
V_Rd	=	40,843	kN
U.C.	=	0,460	-
V_Rd	=	39,853	kN
U.C.	=	0,471	-
V_Rd	=	37,002	kN
U.C.	=	0,507	-
V_Rd	=	32,533	kN
U.C.	=	0,577	-

	U.C. (Bending)		
	Slab #1	Slab #2	Slab #3
t_0 = 0	0,78	0,82	0,80
t_1 = 50	0,82	0,87	0,81
t_2 = 100	0,91	1,01	0,83
t_3 = 150	1,06	1,19	0,86

LC1	from **t_0** till **t_1**
LC2	from **t_1** till **t_2**
LC3	from **t_2** till **t_3**

k	=	3,83	-	carbonation coefficient
r_cor	=	4,44976	µm / year	corrosion rate
V_corr	=	0,00444976	µm / year	
I_corr	=	0,3836	µA / cm2	

	Slab #1			Slab #2			Slab #3		
	BM	SF	Defl	BM	SF	Defl	BM	SF	Defl
t_0	0,782	0,403	0,380	0,817	0,146	0,288	0,803	0,460	0,528
t_1	0,816	0,403	0,380	0,872	0,147	0,288	0,811	0,471	0,528
t_2	-	-	-	1,012	0,150	0,288	0,834	0,507	0,528
t_3	-	-	-	1,188	0,154	0,288	0,864	0,577	0,528

G
Manufacturer Data

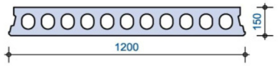
This appendix provides relevant data supplied by manufacturers for the hollow core slabs and deep deck composite slabs. The information includes material specifications, product details, and structural properties essential for the design and analysis of these systems. These manufacturer inputs ensure compliance with industry standards. An overview of the included manufacturer data can be found in Table G.1.

Table G.1: Overview of Manufacturer Data

Page Number	Content Description
122	Manufacturer data of the hollow core slab
123	Manufacturer data of the deep deck composite slab

	d	I	h_mod	ρ	ρ	A	Centre of Gravity
VBI150	150	308100000	145,5114716	268	2,68	126076	74,1
VBI200	200	6,7740E+08	189	308	3,080	143823	99,4
VBI260	260	1,4349E+09	243	383	3,830	177829	122,9
VBI320	320	2,4690E+09	291	429	4,290	198483	152,5
VBI400	400	4,4210E+09	354	490	4,900	225911	190,4
VBI500	500	8,2290E+09	435	601	6,010	278359	237,31
Unit	mm	mm4	mm	kg/m2	kN/m3	mm2	mm

Specificaties

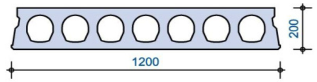


Doorsnede

Technische specificaties	
Gewicht inclusief voegvulling	268 kg/m2
Milieuklasse[1]	XC1en XC3
Brandwerendheid	60 - 90 minuten
Maximum plaatlengte utiliteitsbouw woningbouw (dakvloer)	 8,10 meter 6,75 meter
Pasplaatbreedte	300 + n x 100 mm
Voegvulling	6,5 liter/m1
Sterkteklasse	C40/50
Betondoorsnede	126076 mm2
Zwaartepunt van de doorsnede	74,1 mm
Kwadratisch oppervlaktemoment	308,1 x 10^6 mm4
Bovenzijde van het element	standaard of gebezemd

[1] Vloeren die aan de buitenlucht zijn blootgesteld, moeten voldoen aan de eisen volgens milieuklasse XC3.

Specificaties

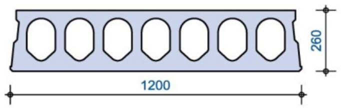


Doorsnede

Technische specificaties	
Gewicht inclusief voegvulling	308 kg/m2
Milieuklasse[1]	XC1 en XC3
Brandwerendheid	maximaal 120 minuten
Maximum plaatlengte woningbouw, verdieping woningbouw, dakvloer utiliteitsbouw	 7,6 meter 9,0 meter 10,0 meter
Plaatbreedte	1,20 meter
Pasplaatbreedte woningbouw [2] utiliteitsbouw	 300 + n x 100 mm 300 + n x 150 mm
Voegvulling	8,1 liter/m1
Sterkteklasse	C45/55
Betondoorsnede	143823 mm2
Zwaartepunt van de doorsnede	99,4 mm
Kwadratisch oppervlaktemoment	677,4 x 10^6 mm4
Bovenzijde van het element	standaard of gebezemd

[1] Vloeren die aan de buitenlucht zijn blootgesteld, moeten voldoen aan de eisen volgens milieuklasse XC3.
[2] Pasplaten worden uitgevoerd in het vloertype Leidingvloer 200.

Specificaties

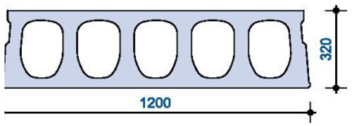


Doorsnede

Technische specificaties	
Gewicht inclusief voegvulling	383 kg/m2
Milieuklasse[1]	XC1, XC3
Brandwerendheid	maximaal 120 minuten
Maximum plaatlengte woningbouw utiliteitsbouw	 10,0 meter 12,6 meter
Plaatbreedte	1,20 meter
Pasplaatbreedte	300 + n x 150 mm
Voegvulling	11,1 liter/m1
Sterkteklasse	C45/55
Betondoorsnede	177829 mm2
Zwaartepunt van de doorsnede	122,9 mm
Kwadratisch oppervlaktemoment	1434,9 x 10^6 mm4
Bovenzijde van het element	standaard of gebezemd

[1] Vloeren die aan de buitenlucht zijn blootgesteld, moeten voldoen aan milieuklasse XC3.

pecificaties

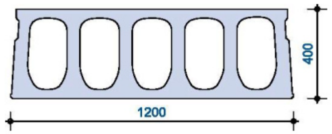


oorsnede

Technische specificaties	
Gewicht inclusief voegvulling	429 kg/m2
Milieuklasse[1]	XC1, XC3
Brandwerendheid	maximaal 120
Maximum plaatlengte	14,7 meter
Plaatbreedte	1,20 meter
Pasplaatbreedte	400 + n x 200 mm
Voegvulling	13,1 liter/m1
Sterkteklasse	C45/55
Betondoorsnede	198483 mm2
Zwaartepunt van de doorsnede	152,5 mm
Kwadratisch oppervlaktemoment	2469 x 10^6 mm4
Bovenzijde van het element	standaard of gebezemd

Vloeren die aan de buitenlucht zijn blootgesteld, moeten voldoen aan milieuklasse XC3.

Specificaties

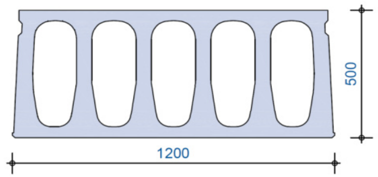


Doorsnede

Technische specificaties	
Gewicht inclusief voegvulling	490 kg/m2
Milieuklasse[1]	XC1, XC3
Brandwerendheid	maximaal 120 minuten
Maximum plaatlengte	18 meter
Plaatbreedte	1,20 meter
Pasplaatbreedte	400 + n x 200 mm
Voegvulling	15,8 liter/m1
Sterkteklasse	C45/55
Betondoorsnede	225911 mm2
Zwaartepunt van de doorsnede	190,4 mm
Kwadratisch oppervlaktemoment	4421 x 10^6 mm4
Bovenzijde van het element	standaard of gebezemd

[1] Vloeren die aan de buitenlucht zijn blootgesteld, moeten voldoen aan milieuklasse XC3.

Specificaties



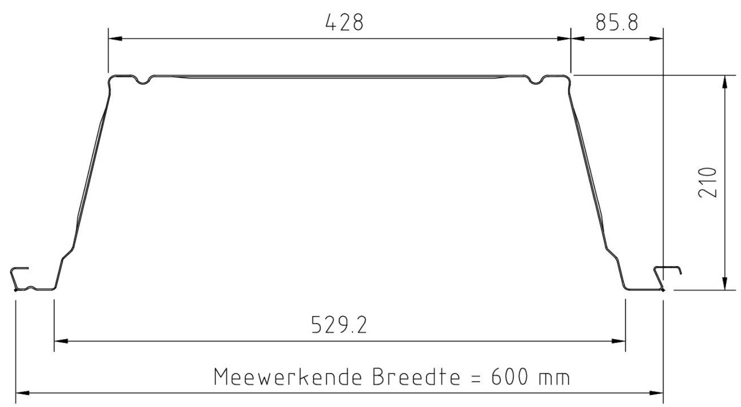
Doorsnede

Technische specificaties	
Gewicht incl. voegvulling	601 kg/m2
Milieuklasse[1]	XC1, XC3
Brandwerendheid	maximaal 120 minuten
Maximum plaatlengte	20,00 meter
Plaatbreedte	1,20 meter
Pasplaatbreedte	400, 600, 800, 1000 mm
Voegvulling	18,3 liter/m1
Sterkteklasse	C45/55
Betondoorsnede	278359 mm2
Zwaartepunt van de doorsnede	237,31 mm
Kwadratisch oppervlaktemoment	8229 x 10^6 mm4
Bovenzijde van het element	standaard of gebezemd

[1] Voor vloeren die aan de buitenlucht zijn blootgesteld gelden de eisen behorende bij milieuklasse XC3.

Vloerdikte [mm]	Eigen Gewicht [kg/m2]	Eigen Gewicht [kN/m2]	Eigen Gewicht Beton [kN/m2]	Eigen Gewicht Plaat [kN/m2]	Netto Beton Volume [l/m2]	Netto Beton Volume [m3/m2]	Eigen Gewicht Plaat [kg/m2]
270	267	2,67	2,54	0,13	101	0,101	13
280	291	2,91	2,78	0,13	111	0,111	13
290	315	3,15	3,02	0,13	121	0,121	13
300	339	3,39	3,26	0,13	131	0,131	13
310	363	3,63	3,50	0,13	141	0,141	13
320	387	3,87	3,74	0,13	151	0,151	13
330	411	4,11	3,98	0,13	161	0,161	13
340	435	4,35	4,22	0,13	171	0,171	13
350	459	4,59	4,46	0,13	181	0,181	13

https://www.dutchengineering.nl/producten/comflor-210/



Doorsnedegrootheden ComFlor 210+						
Nominale dikte	Kerndikte	Gewicht	Oppervlak	Traagheidsmoment	Maximaal moment	
					veld	steunpunt
[mm]	[mm]	[kN/m^2]	[mm^2/m]	[mm^4/m]	[kNm/m]	[kNm/m]
1,00	0,96	0,13	1627	7460000	15,30	22,90
1,25	1,21	0,16	2051	9790000	21,90	34,00
1,50	1,46	0,19	2475	11700000	28,50	40,80

ComFlor 210+ Staalplaat-betonvloer					
Vloerdikte	Netto Beton-volume 1)	Eigen gewicht Staalplaat-betonvloer 1+2) Grindbeton	Max. stempelvrije overspanning 3)		
			1.00 mm	1.25 mm	1.50 mm
			Enkelvelds	Enkelvelds	Enkelvelds
[mm]	[l/m^2]	[kg/m^2]	[m]	[m]	[m]
260	96	243	4,90	5,80	6,15
270	106	267	4,75	5,65	6,00
280	116	291	4,65	5,50	5,90
290	126	315	4,55	5,35	5,80
300	136	339	4,45	5,25	5,70
310	146	363	4,35	5,15	5,60
320	156	387	4,25	5,05	5,55
330	166	411	4,15	4,95	5,45
340	176	435	4,10	4,85	5,40
350	186	459	4,00	4,75	5,35

1) Exclusief doorbuiging staalplaat en liggers tijdens uitvoering - exclusief eventueel extra beton boven opleggingen. Reductie betonvolume door profilering: 169 l/m^2
Eigen gewicht staalplaat-betonvloer is gebaseerd op een plaat van 1,0 mm dikte.

2) Aangehouden soortelijk gewicht beton:
Grindbeton: 2.400 kg/m^3

3) Doorbuiging staalplaat maximaal 20 mm: extra betonvolume maximaal 12 l/m^2 - extra eigen gewicht maximaal 29 kg/m^2 (grindbeton). Aangegeven overspanning is stramienmaat - aangehouden oplegbreedte 200 mm.

H

Set A2 Results

This appendix presents the results for Set A2, which includes 19 environmental impact categories and the Environmental Cost Indicator (ECI). These categories are expected to become mandatory in 2025, emphasizing the importance of their inclusion in this analysis. The results are detailed for each slab type and are provided for a single life cycle, as well as for two and three life cycles, enabling a thorough exploration of the environmental impacts over different scenarios. Although set A1 remains the currently established framework, the inclusion of set A2 results here offers insight into an alternative methodology under evaluation for future applications. An overview of the tables included in this appendix is provided in Table H.1 for reference.

Table H.1: Overview of Tables in Set A2 Results Appendix

Table Name	Description
Table H.2	EI of Slab 1 (Set A2)
Table H.3	EI of Slab 2 (Set A2)
Table H.4	EI of Slab 3 (Set A2)
Table H.5	Comparison of EI Across Slabs for a Single Life Cycle (Set A2)
Table H.6	Comparison of EI Across Slabs for Two Life Cycles (Set A2)
Table H.7	Comparison of EI Across Slabs for Three Life Cycles (Set A2)

Table H.2: EI of Slab 1 (Set A2)

Set A2	**A1 - A3**	**A4 - A5**	**C1 - C4**	**D**	**Total**
Global Warming Potential total	3.93E1	4.62E0	6.43E0	-2.79E0	4.75E1
Global Warming Potential fossil fuels	3.85E1	4.61E0	6.43E0	-2.80E0	4.67E1
Global Warming Potential biogenic	7.00E-1	4.21E-3	-6.08E-3	1.89E-2	7.15E-1
Global Warming Potential land use	3.05E-2	2.60E-3	1.91E-3	-8.86E-5	3.49E-2
Depletion potential of the stratospheric ozone layer	1.72E-6	7.98E-7	1.29E-6	-1.65E-7	3.64E-6
Acidification potential	1.44E-1	3.03E-2	5.37E-2	-1.44E-2	2.14E-1
Eutrophication potential, freshwater	2.25E-3	1.03E-4	7.28E-5	7.55E-6	2.44E-3
Eutrophication potential, marine	3.59E-2	1.11E-2	2.14E-2	-3.63E-3	6.48E-2
Eutrophication potential, terrestrial	3.97E-1	1.21E-1	2.36E-1	-4.52E-2	7.08E-1
Formation potential of tropospheric ozone	1.33E-1	3.55E-2	6.56E-2	-1.85E-2	2.15E-1
Abiotic depletion potential for non-fossil resources	2.04E-4	6.99E-5	8.73E-5	-6.64E-5	2.95E-4
Abiotic depletion for fossil resources potential	3.60E2	6.54E1	9.22E1	-2.62E1	4.92E2
Water (user) deprivation potential	1.81E1	6.58E-1	3.11E-1	-2.06E1	-1.48E0
Potential incidence of disease due to PM emissions	2.27E-6	6.08E-7	1.19E-6	-2.72E-7	3.80E-6
Potential Human exposure efficiency relative to U235	1.05E0	2.47E-1	3.75E-1	-2.05E-2	1.65E0
Potential Comparative Toxic Unit for ecosystems	7.20E2	5.60E1	7.56E1	-4.58E1	8.06E2
Potential Comparative Toxic Unit for humans	2.41E-7	1.34E-8	2.63E-9	1.28E-8	2.70E-7
Potential Comparative Toxic Unit for humans	2.42E-6	1.62E-7	8.55E-8	3.41E-7	3.01E-6
Potential soil quality index	2.16E2	3.96E1	4.88E1	-2.41E1	2.80E2

Table H.3: EI of Slab 2 (Set A2)

Set A2 (Slab 2)	**A1 - A3**	**A4 - A5**	**C1 - C4**	**D**	**Total**
Global Warming Potential total	2.85E+1	2.93E+0	1.79E+0	-2.05E+0	3.12E+1
Global Warming Potential fossil fuels	2.87E+1	2.79E+0	1.80E+0	-2.07E+0	3.12E+1
Global Warming Potential biogenic	-2.07E-1	1.36E-1	4.86E-4	1.47E-2	-5.57E-2
Global Warming Potential land use and land use change	1.76E-2	1.52E-3	7.80E-4	1.72E-4	2.01E-2
Depletion potential of the stratospheric ozone layer	1.05E-6	4.67E-7	3.43E-7	-1.08E-7	1.75E-6
Acidification potential	9.24E-2	1.12E-2	1.19E-2	-9.98E-3	1.05E-1
Eutrophication potential, freshwater	1.61E-3	6.72E-5	2.67E-5	-1.97E-5	1.69E-3
Eutrophication potential, marine	2.72E-2	3.22E-3	4.29E-3	-2.36E-3	3.24E-2
Eutrophication potential, terrestrial	3.10E-1	3.56E-2	4.73E-2	-2.91E-2	3.64E-1
Formation potential of tropospheric ozone	8.73E-2	1.18E-2	1.34E-2	-1.30E-2	9.94E-2
Abiotic depletion potential for non-fossil resources	1.13E-4	3.44E-5	3.80E-5	-3.37E-5	1.52E-4
Abiotic depletion for fossil resources potential	2.17E+2	3.77E+1	2.63E+1	-1.87E+1	2.62E+2
Water deprivation potential	5.12E+0	7.80E-1	1.20E-1	-9.97E+0	-3.94E+0
Potential incidence of disease due to PM emissions	1.11E-6	2.53E-7	2.15E-7	-1.81E-7	1.40E-6
Potential Human exposure efficiency relative to U235	6.35E-1	1.45E-1	1.03E-1	-8.43E-3	8.74E-1
Potential Comparative Toxic Unit for ecosystems	2.44E+2	3.91E+1	2.22E+1	-4.41E+1	2.62E+2
Potential Comparative Toxic Unit for humans	1.12E-7	5.37E-9	8.25E-10	5.16E-9	1.23E-7
Potential Comparative Toxic Unit for humans	7.73E-7	4.33E-8	2.86E-8	2.37E-7	1.08E-6
Potential soil quality index	2.83E+2	3.58E+1	2.01E+1	-1.88E+1	3.20E+2

Table H.4: EI of Slab 3 (Set A2)

Set A2 (Slab 3)	**A1 - A3**	**A4 - A5**	**C1 - C4**	**D**	**Total**
Global Warming Potential total	3.66E1	3.20E0	1.90E0	-1.43E0	4.03E1
Global Warming Potential fossil fuels	3.65E1	3.19E0	1.90E0	-1.43E0	4.01E1
Global Warming Potential biogenic	6.14E-2	4.68E-3	-1.89E-3	1.54E-3	6.58E-2
Global Warming Potential land use	7.01E-2	8.15E-3	5.30E-3	-2.96E-3	8.06E-2
Depletion potential of the stratospheric ozone layer	3.30E-7	4.23E-8	3.46E-8	-2.37E-8	3.83E-7
Acidification potential	1.53E-1	1.44E-2	1.15E-2	-7.27E-3	1.72E-1
Eutrophication potential, freshwater	2.38E-3	9.44E-5	3.21E-5	-7.81E-5	2.43E-3
Eutrophication potential, marine	3.79E-2	4.64E-3	3.91E-3	-1.91E-3	4.45E-2
Eutrophication potential, terrestrial	4.56E-1	5.25E-2	4.24E-2	-2.17E-2	5.29E-1
Formation potential of tropospheric ozone	1.31E-1	1.65E-2	1.38E-2	-8.10E-3	1.54E-1
Abiotic depletion potential for non-fossil resources	9.01E-5	9.05E-6	2.37E-5	-4.41E-6	1.18E-4
Abiotic depletion for fossil resources potential	2.80E2	3.46E1	2.70E1	-1.57E1	3.26E2
Water (user) deprivation potential	1.05E1	4.90E-1	2.07E-1	-6.63E-1	1.05E1
Potential incidence of disease due to PM emissions	2.24E-6	2.49E-7	2.19E-7	-1.54E-7	2.55E-6
Potential Human exposure efficiency relative to U235	5.91E-1	3.15E-2	2.22E-2	-2.61E-2	6.19E-1
Potential Comparative Toxic Unit for ecosystems	2.22E2	2.53E1	1.87E1	-6.56E0	2.60E2
Potential Comparative Toxic Unit for humans	3.13E-7	1.12E-8	1.25E-9	-7.85E-9	3.18E-7
Potential Comparative Toxic Unit for humans	1.16E-6	6.04E-8	3.77E-8	-1.22E-8	1.24E-6
Potential soil quality index	1.31E2	2.44E1	2.34E1	-1.11E1	1.68E2

Table H.5: Comparison of EI Across Slabs for a Single Life Cycle (Set A2)

SET A2	**Slab 1**	**Slab 2**	**Slab 3**
Global Warming Potential total	4.75E+01	3.12E+01	4.03E+01
Global Warming Potential fossil fuels	4.67E+01	3.12E+01	4.01E+01
Global Warming Potential biogenic	7.15E-01	-5.57E-02	6.58E-02
Global Warming Potential land use	3.49E-02	2.01E-02	8.06E-02
Depletion potential of the stratospheric ozone layer	3.64E-06	1.75E-06	3.83E-07
Acidification potential	2.14E-01	1.05E-01	1.72E-01
Eutrophication potential, freshwater	2.44E-03	1.69E-03	2.43E-03
Eutrophication potential, marine	6.48E-02	3.24E-02	4.45E-02
Eutrophication potential, terrestrial	7.08E-01	3.64E-01	5.29E-01
Formation potential of tropospheric ozone	2.15E-01	9.94E-02	1.54E-01
Abiotic depletion potential for non-fossil resources	2.95E-04	1.52E-04	1.18E-04
Abiotic depletion for fossil resources potential	4.92E+02	2.62E+02	3.26E+02
Water (user) deprivation potential	-1.48E+00	-3.94E+00	1.05E+01
Potential incidence of disease due to PM emissions	3.80E-06	1.40E-06	2.55E-06
Potential Human exposure efficiency relative to U235	1.65E+00	8.74E-01	6.19E-01
Potential Comparative Toxic Unit for ecosystems	8.06E+02	2.62E+02	2.60E+02
Potential Comparative Toxic Unit for humans	2.70E-07	1.23E-07	3.18E-07
Potential Comparative Toxic Unit for humans	3.01E-06	1.08E-06	1.24E-06
Potential soil quality index	2.80E+02	3.20E+02	1.68E+02
Environmental Cost Indicator	**€9.53**	**€5.26**	**€7.45**

Table H.6: Comparison of EI Across Slabs for Two Life Cycles (Set A2)

SET A2	**Slab 1 (LE)**		**Slab 2 (CE)**		**Slab 3 (CE)**	
	LC1	**LC2**	**LC1**	**LC2**	**LC1**	**LC2**
GWP-total	4.75E+01	4.75E+01	3.15E+01	2.67E+00	3.98E+01	3.68E+00
GWP-fossil	4.67E+01	4.67E+01	3.15E+01	2.51E+00	3.97E+01	3.66E+00
GWP-biogenic	7.15E-01	7.15E-01	-7.08E-02	1.51E-01	6.61E-02	4.33E-03
GWP-luluc	3.49E-02	3.49E-02	1.91E-02	2.47E-03	7.82E-02	1.05E-02
ODP	3.64E-06	3.64E-06	1.52E-06	7.02E-07	3.72E-07	5.32E-08
AP	2.14E-01	2.14E-01	1.04E-01	1.31E-02	1.68E-01	1.86E-02
EP-freshwater	2.44E-03	2.44E-03	1.68E-03	7.41E-05	2.47E-03	4.83E-05
EP-marine	6.48E-02	6.48E-02	3.04E-02	5.15E-03	4.25E-02	6.64E-03
EP-terrestrial	7.08E-01	7.08E-01	3.46E-01	5.39E-02	5.08E-01	7.32E-02
POCP	2.15E-01	2.15E-01	9.91E-02	1.21E-02	1.48E-01	2.23E-02
ADP-minerals&metals	2.95E-04	2.95E-04	1.48E-04	3.87E-05	9.92E-05	2.83E-05
ADP-fossil	4.92E+02	4.92E+02	2.55E+02	4.53E+01	3.14E+02	4.58E+01
WDP	-1.48E+00	-1.48E+00	5.90E+00	-9.06E+00	1.09E+01	3.31E-02
PM	3.80E-06	3.80E-06	1.36E-06	2.87E-07	2.49E-06	3.14E-07
IRP	1.65E+00	1.65E+00	7.79E-01	2.39E-01	6.23E-01	2.76E-02
ETP-fw	8.06E+02	8.06E+02	2.83E+02	1.72E+01	2.47E+02	3.74E+01
HTP-c	2.70E-07	2.70E-07	1.17E-07	1.14E-08	3.25E-07	4.58E-09
HTP-nc	3.01E-06	3.01E-06	8.16E-07	3.09E-07	1.22E-06	8.58E-08
SQP	2.80E+02	2.80E+02	3.19E+02	3.71E+01	1.55E+02	3.67E+01
ECI	**€9.53**	**€9.53**	**€5.26**	**€0.57**	**€7.34**	**€0.73**

Table H.7: Comparison of EI Across Slabs for Three Life Cycles (Set A2)

Category	Slab 1 (LE)	Slab 2 (CE)	Slab 3 (CE)
ADP-minerals&metals	6.50E-04	2.06E-04	2.25E-05
ADP-fossil	6.81E-01	1.71E-01	8.83E-02
GWP-total	1.14E+02	3.44E+01	1.46E+01
ODP	1.01E-05	2.59E-06	1.63E-06
POCP	7.32E-02	1.24E-02	5.88E-03
AP	4.75E-01	9.28E-02	8.45E-02
EP	8.53E-02	1.96E-02	1.39E-02
HTP	4.24E+01	8.19E+00	4.30E+00
FAETP	1.41E+00	3.91E-01	1.17E-01
MAETP	3.53E+03	8.34E+02	7.17E+02
TETP	2.96E+00	5.25E-01	7.09E-02
ECI (€)	**13.03**	**3.18**	**1.68**

I

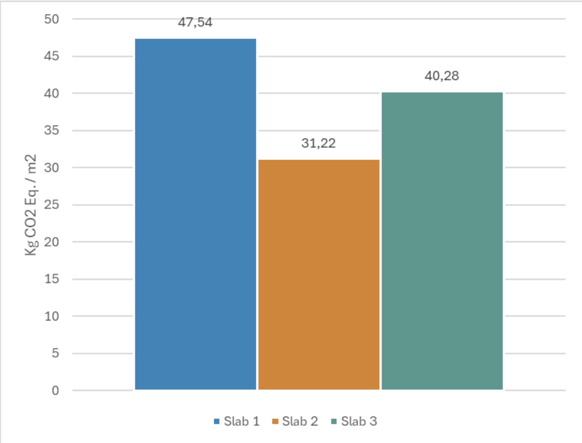
Set A2 EI Result Graphs

This appendix presents the environmental impact results for each slab across various environmental impact categories of the A2 set. The results are divided into three sections: first, the single life cycle results, followed by the results for multi-life cycle assessments (MLCA), specifically for two and three life cycles. An overview of the included graphs in this appendix is can be found in Table I.1.

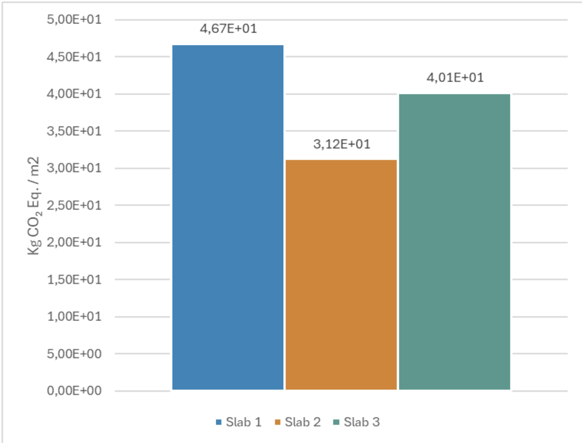
Table I.1: Overview of Graphs

Page Number	Content Description
132	Environmental Impact Result Graphs for a Single Life Cycle
135	Environmental Impact Result Graphs for 2 Life Cycles
138	Environmental Impact Result Graphs for 3 Life Cycles

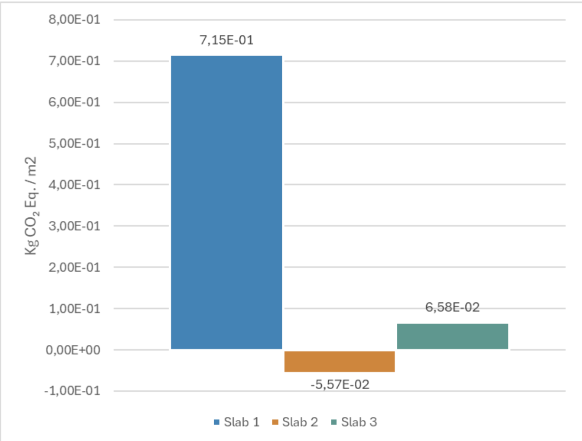
I.1. Single Life Cycle



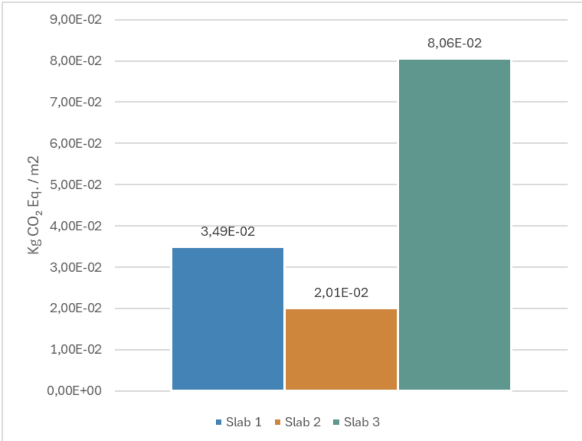
(a) Global Warming Potential Total



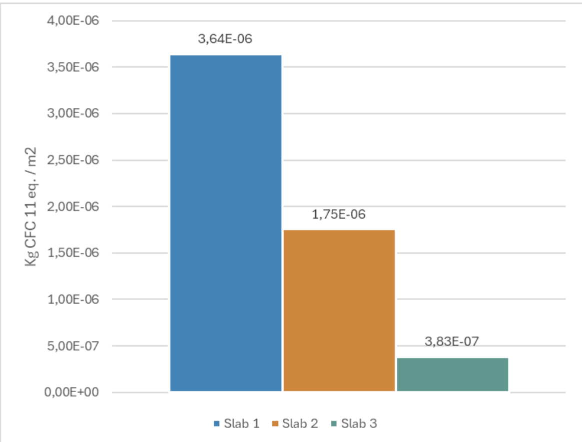
(b) Global Warming Potential Fossil Fuels



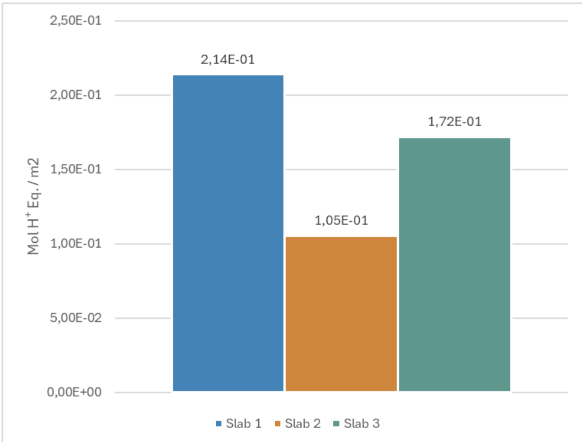
(c) Global Warming Potential Biogenic



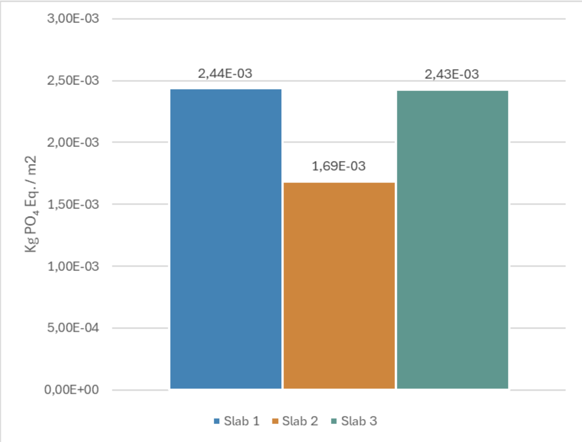
(d) Global Warming Potential Land Use



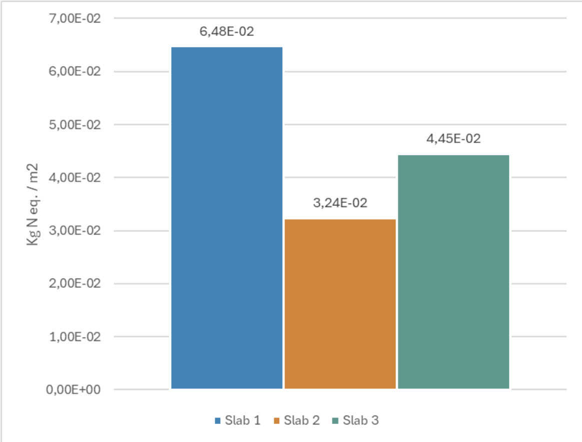
(e) Ozone Layer Depletion Potential



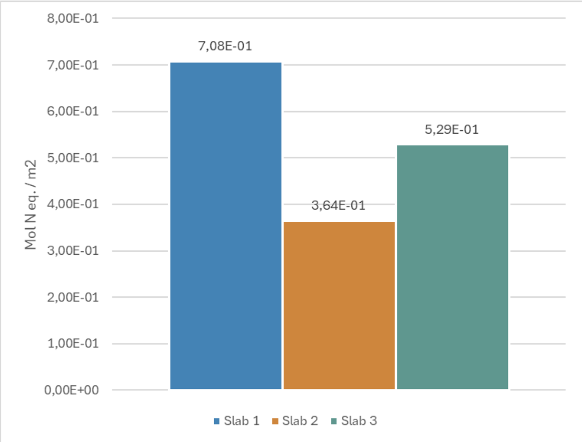
(f) Acidification Potential



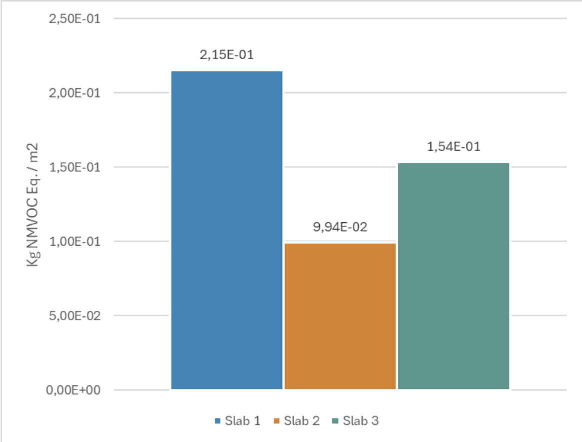
(g) Eutrophication Potential Freshwater



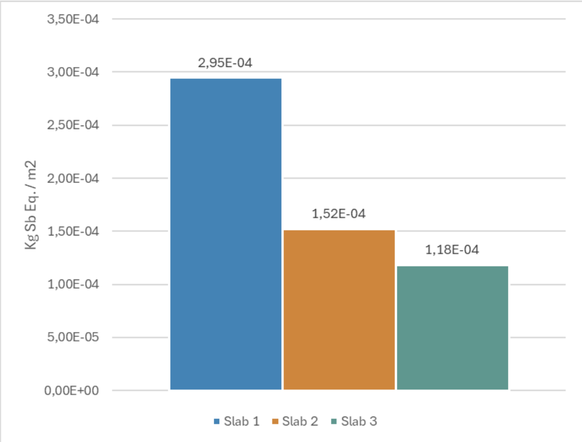
(h) Eutrophication Potential Marine



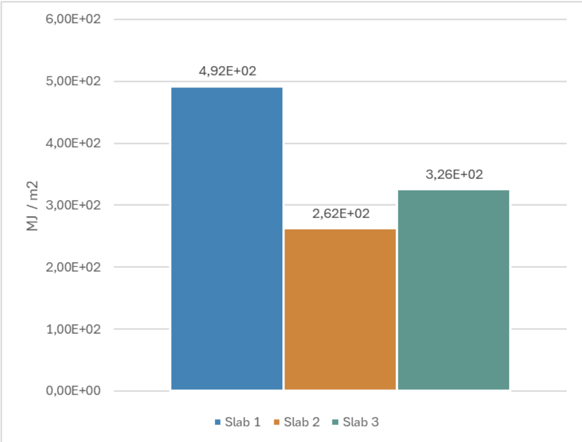
(i) Eutrophication Potential Terrestrial



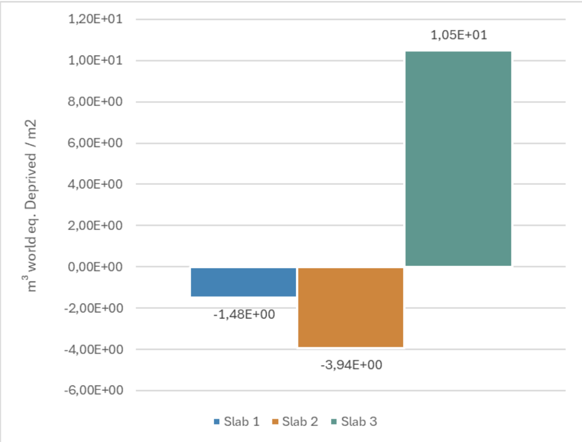
(j) Photochemical Oxidation Potential



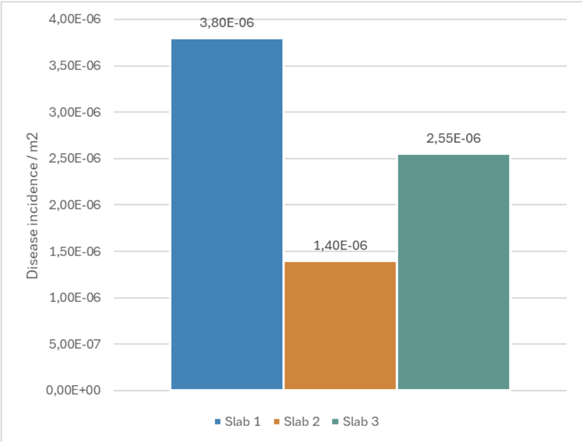
(k) Abiotic Depletion Potential Minerals and Metals



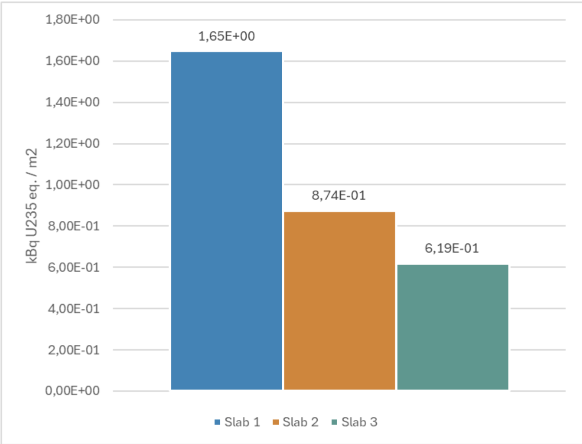
(l) Abiotic Depletion Potential Fossil Fuels



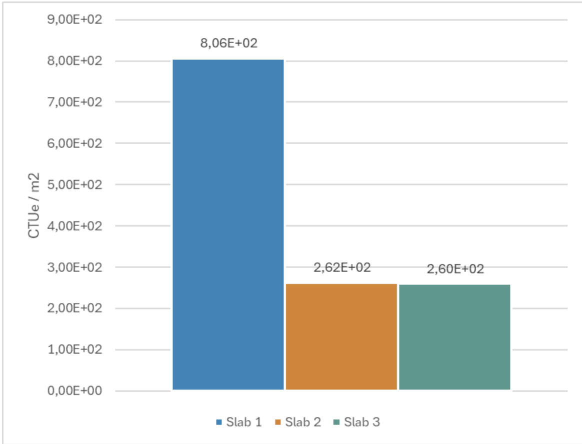
(m) Water (user) Deprivation Potential



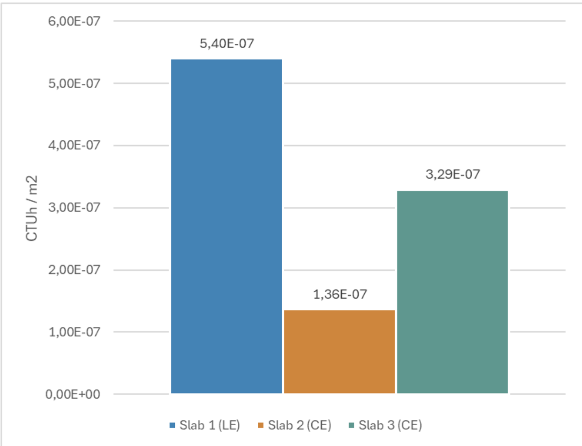
(n) Potential Incidence of Disease due to PM Emissions



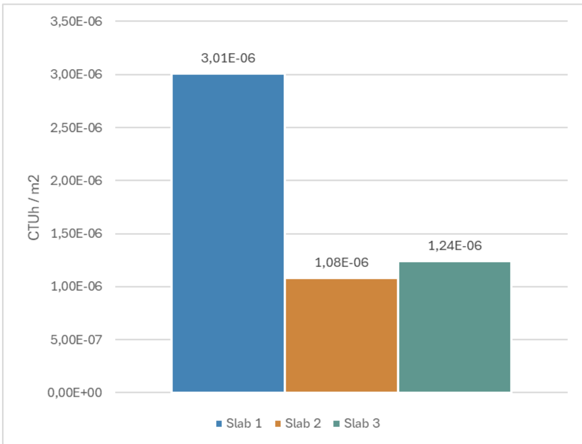
(o) Potential Human Exposure Efficiency Relative to U235



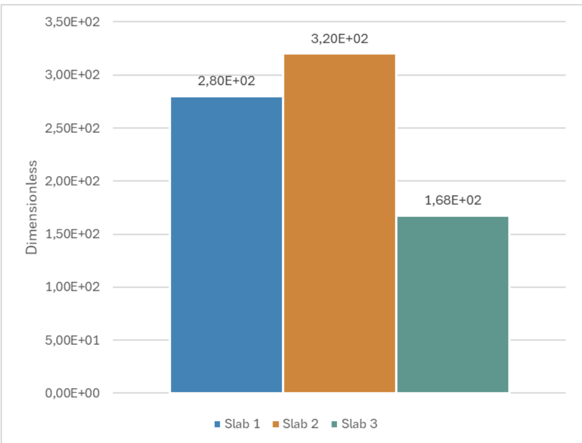
(p) Freshwater Aquatic Ecotoxicity Potential



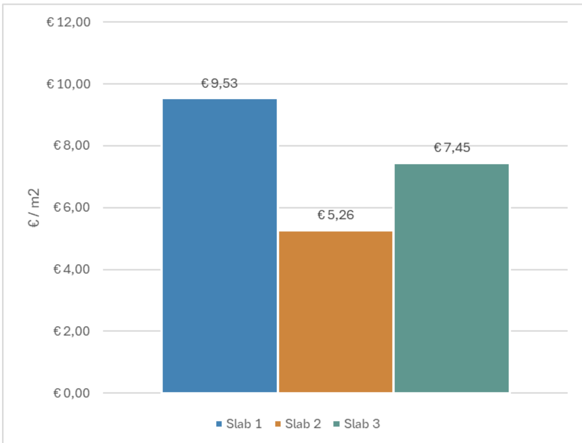
(q) Human Toxicity Potential Carcinogenic



(r) Human Toxicity Potential Non-Carcinogenic



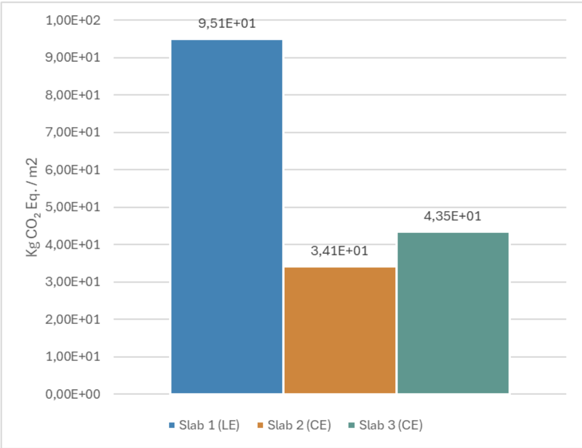
(s) Potential Soil Quality Index



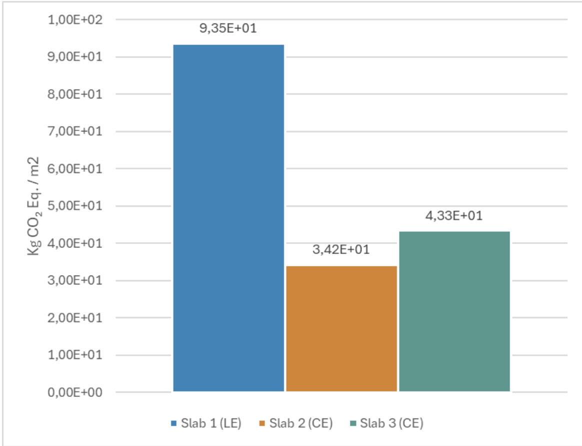
(t) Environmental Cost Indicator

Figure I.1: Environmental Impact over a Single Life Cycles for Set A2

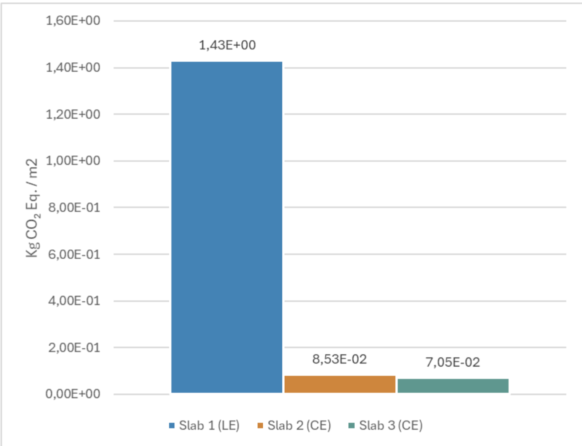
I.2. Two Life Cycles



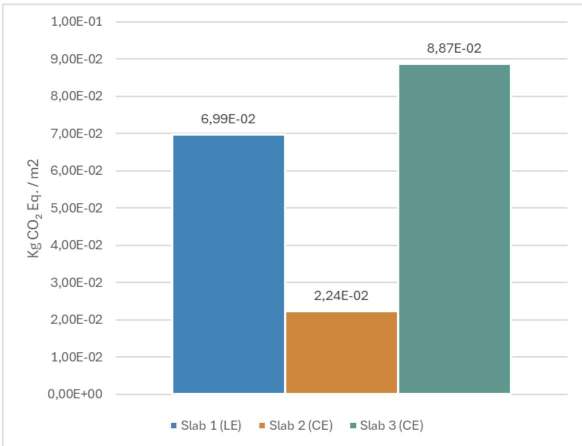
(a) Global Warming Potential Total



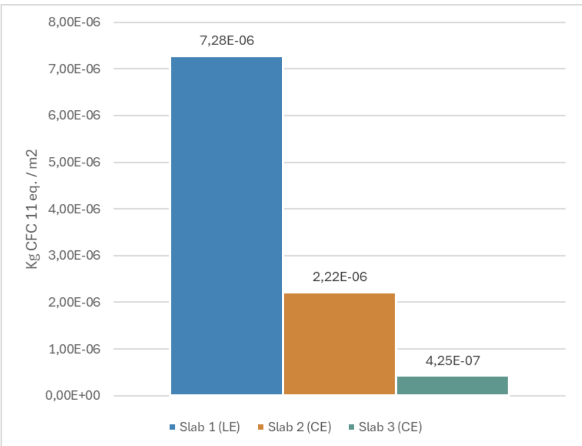
(b) Global Warming Potential Fossil Fuels



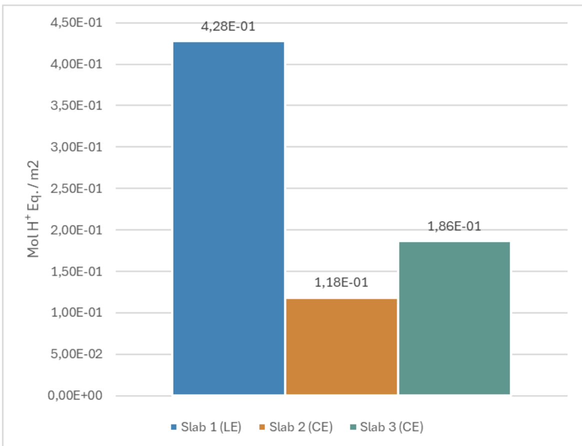
(c) Global Warming Potential Biogenic



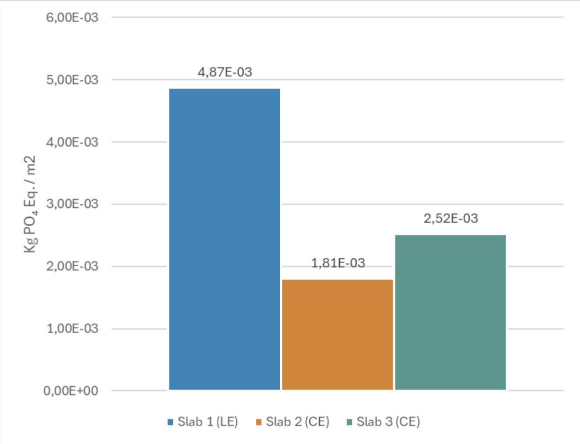
(d) Global Warming Potential Land Use



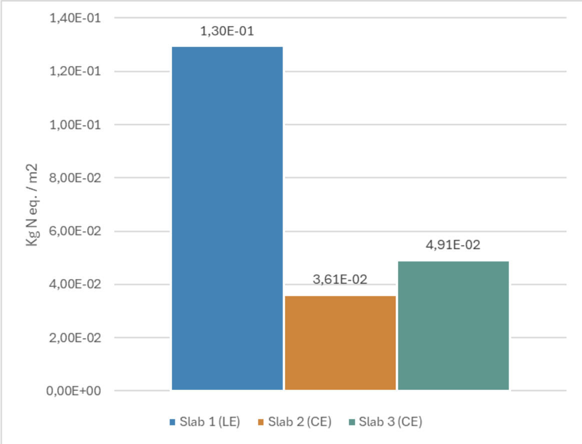
(e) Ozone Layer Depletion Potential



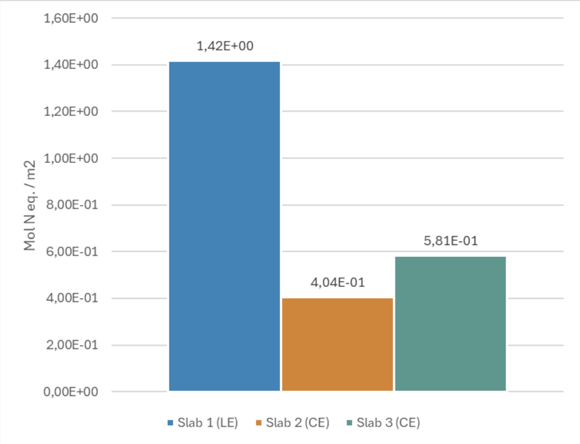
(f) Acidification Potential



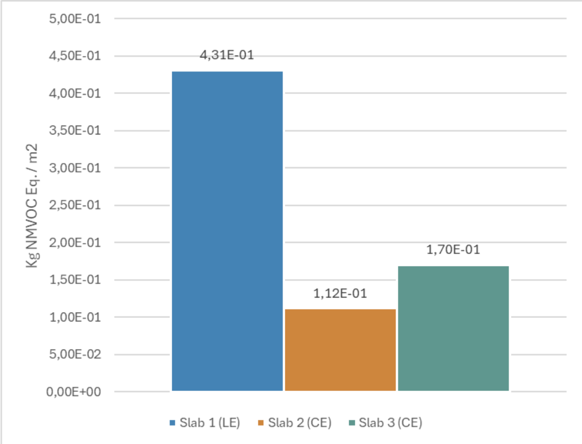
(g) Eutrophication Potential Freshwater



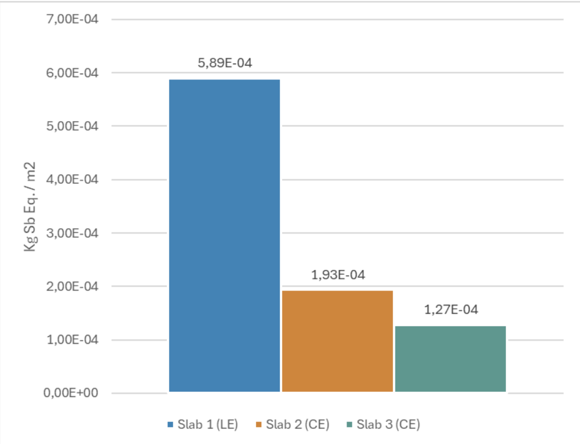
(h) Eutrophication Potential Marine



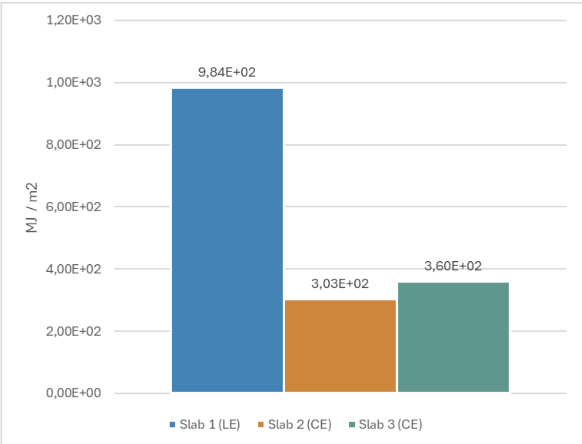
(i) Eutrophication Potential Terrestrial



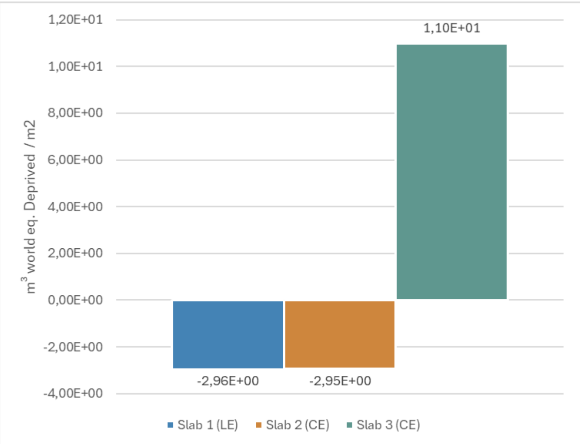
(j) Photochemical Oxidation Potential



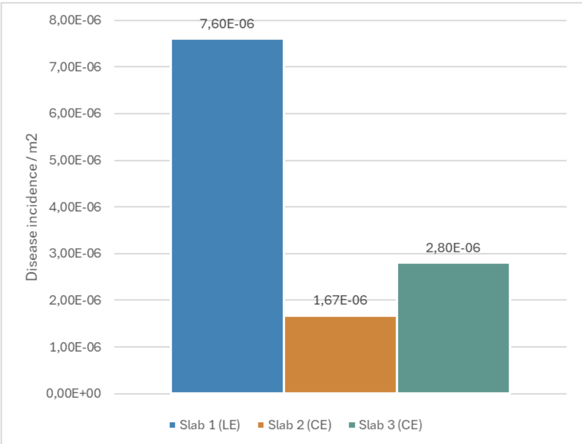
(k) Abiotic Depletion Potential Minerals and Metals



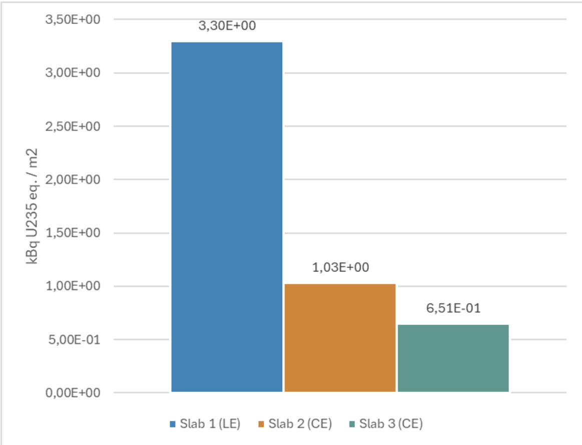
(l) Abiotic Depletion Potential Fossil Fuels



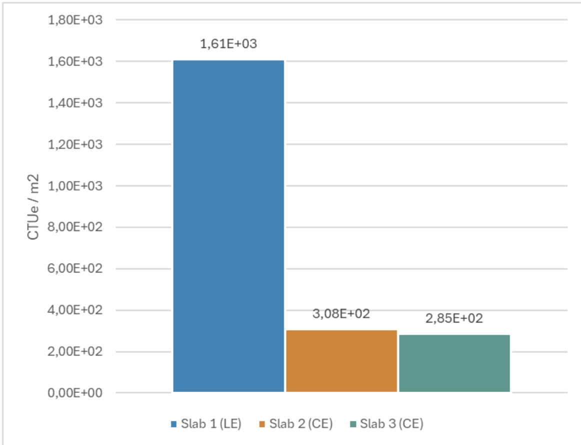
(m) Water (user) Deprivation Potential



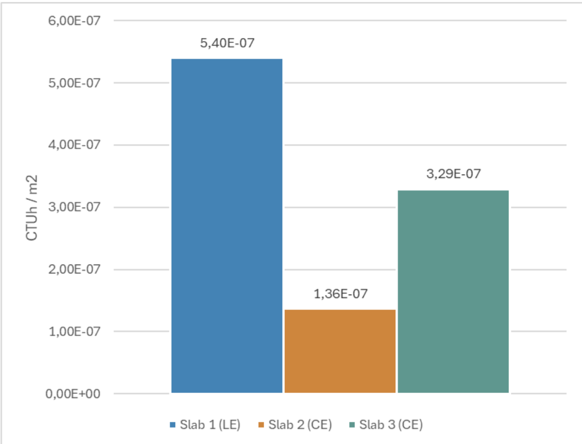
(n) Potential Incidence of Disease due to PM Emissions



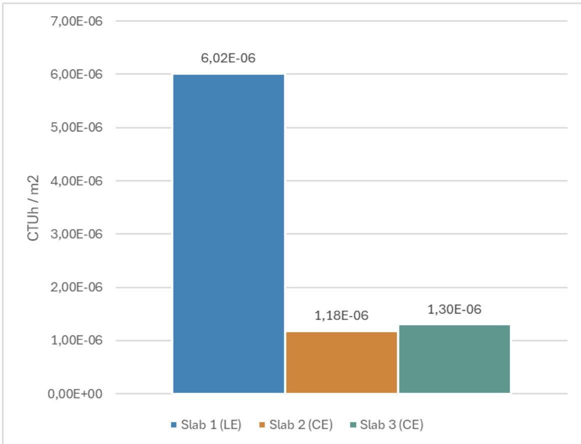
(o) Potential Human Exposure Efficiency Relative to U235



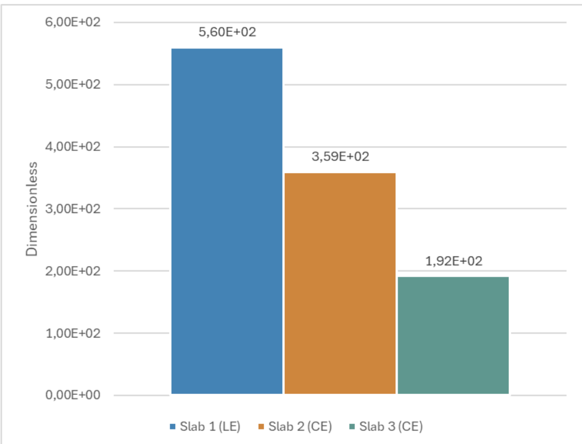
(p) Freshwater Aquatic Ecotoxicity Potential



(q) Human Toxicity Potential Carcinogenic



(r) Human Toxicity Potential Non-Carcinogenic

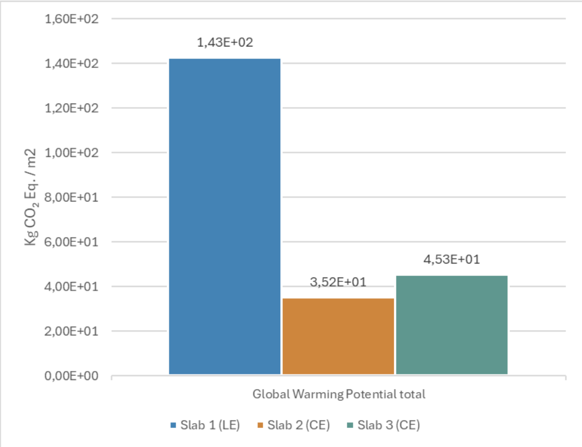


(s) Potential Soil Quality Index

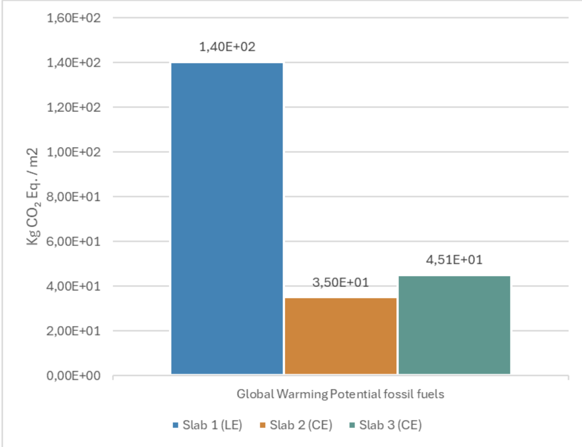
(t) Environmental Cost Indicator

Figure I.2: Environmental Impact over Two Life Cycles for Set A2

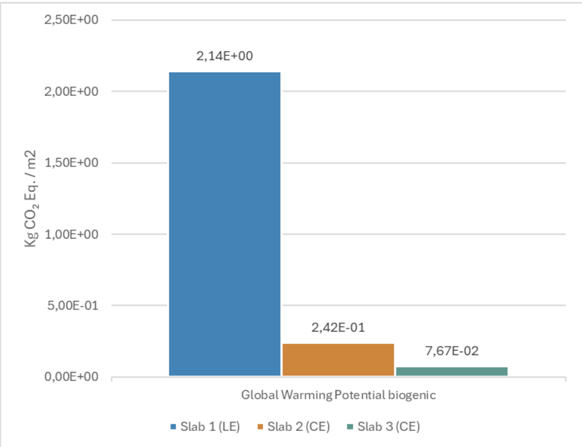
I.3. Three Life Cycles



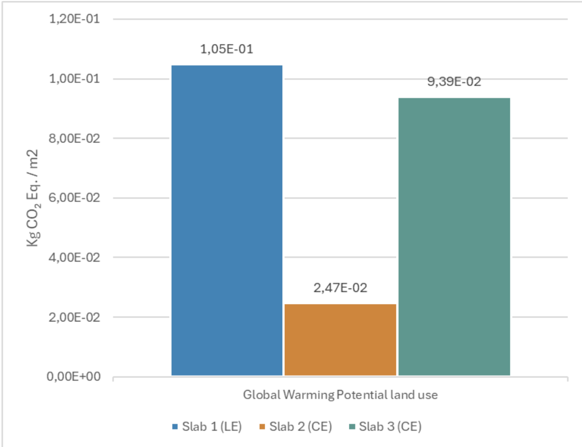
(a) Global Warming Potential Total



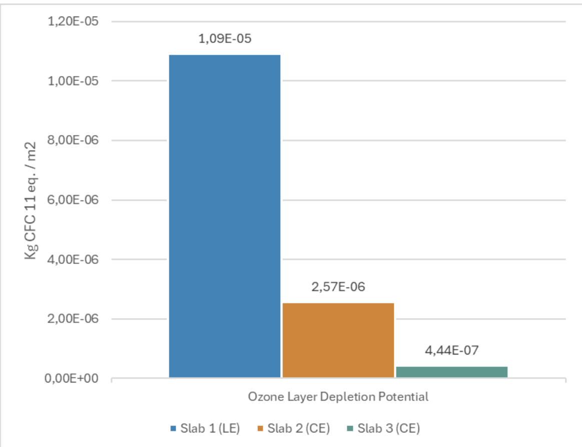
(b) Global Warming Potential Fossil Fuels



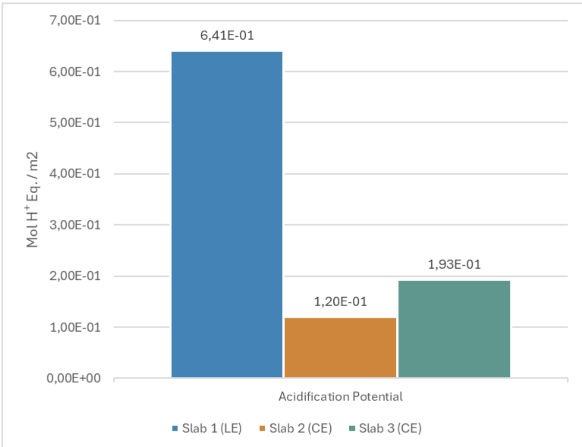
(c) Global Warming Potential Biogenic



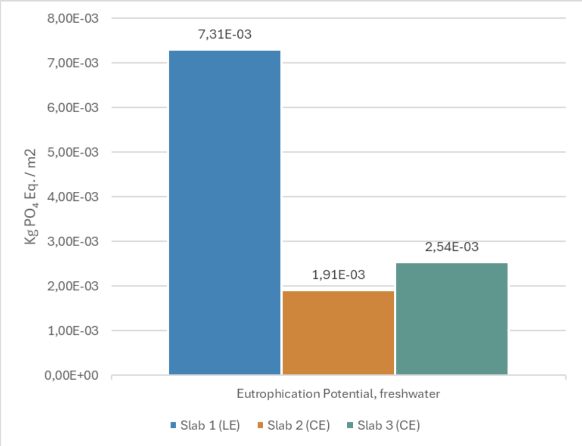
(d) Global Warming Potential Land Use



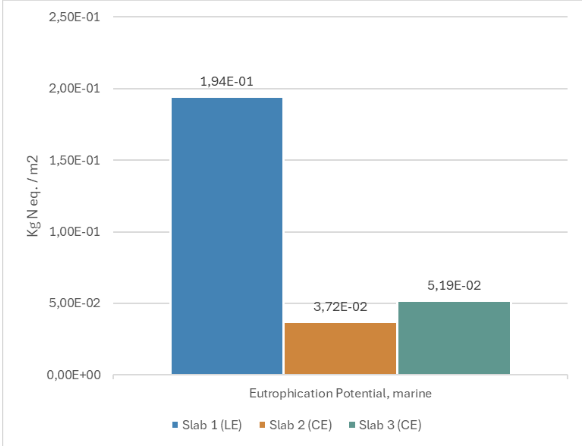
(e) Ozone Layer Depletion Potential



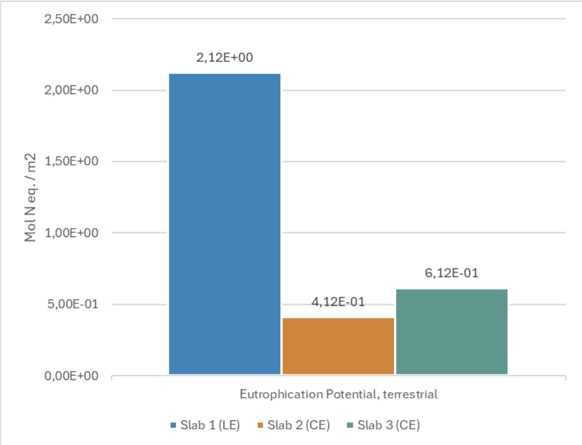
(f) Acidification Potential



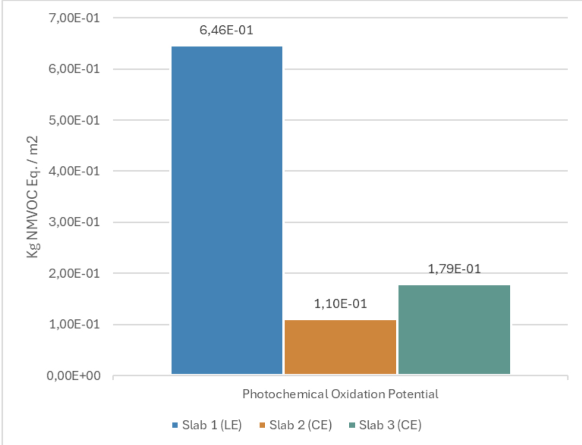
(g) Eutrophication Potential Freshwater



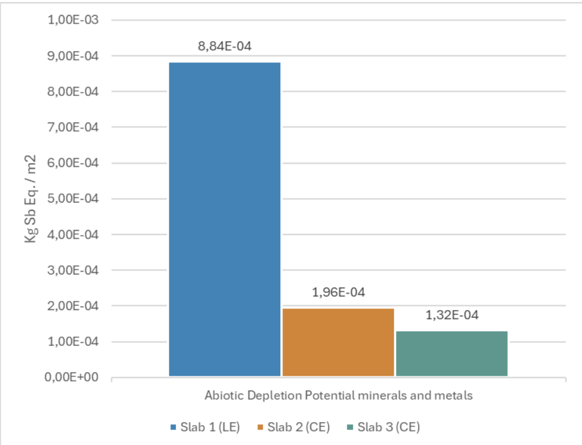
(h) Eutrophication Potential Marine



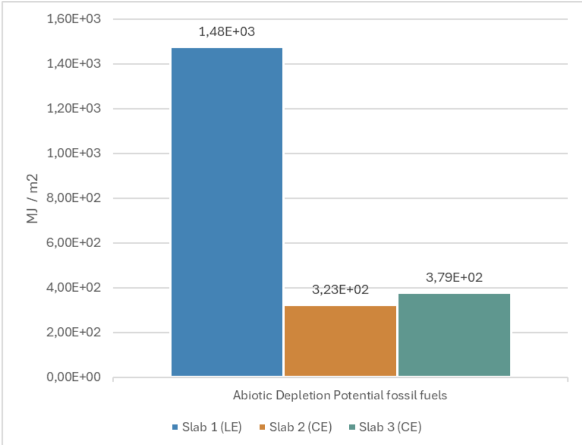
(i) Eutrophication Potential Terrestrial



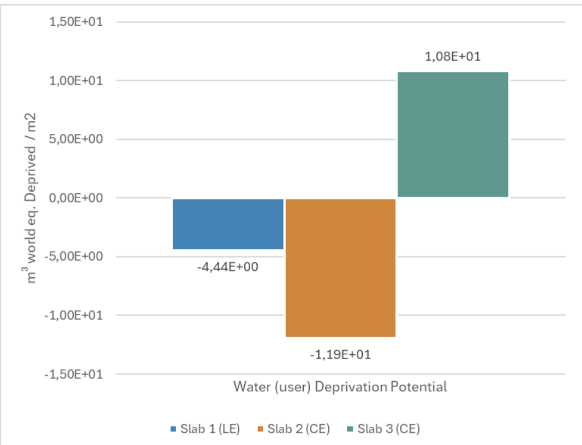
(j) Photochemical Oxidation Potential



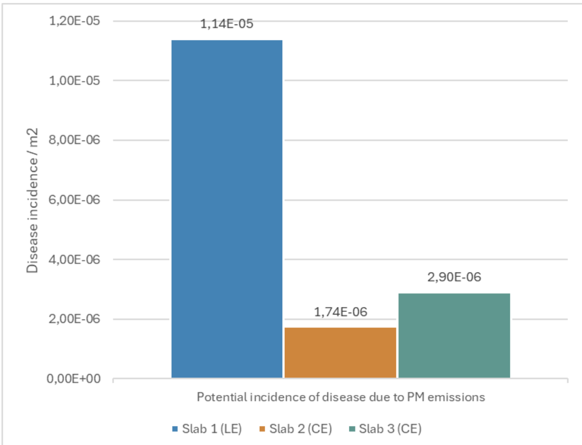
(k) Abiotic Depletion Potential Minerals and Metals



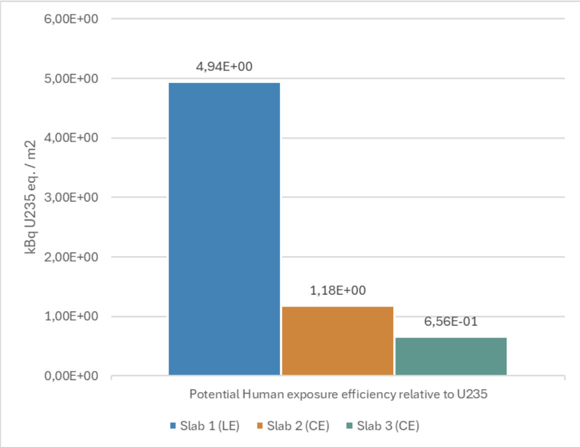
(l) Abiotic Depletion Potential Fossil Fuels



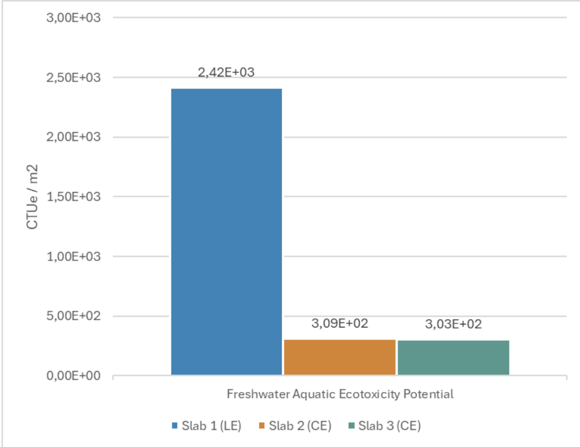
(m) Water (user) Deprivation Potential



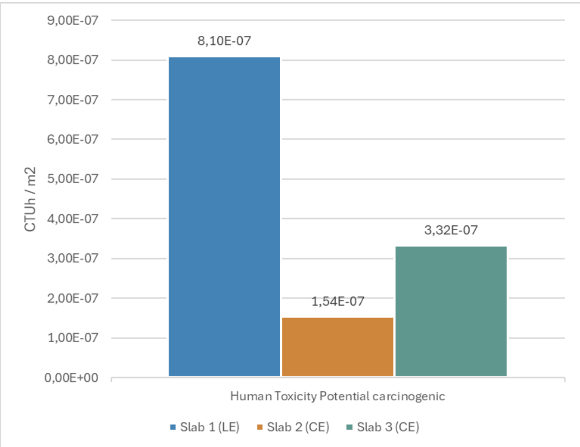
(n) Potential Incidence of Disease due to PM Emissions



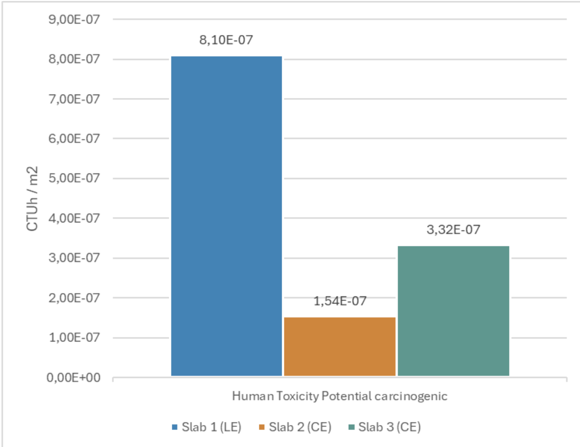
(o) Potential Human Exposure Efficiency Relative to U235



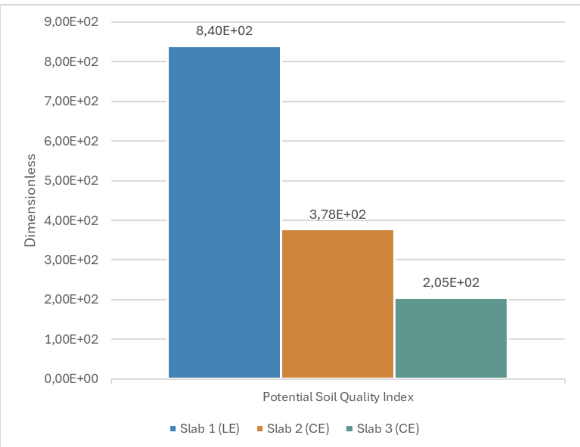
(p) Freshwater Aquatic Ecotoxicity Potential



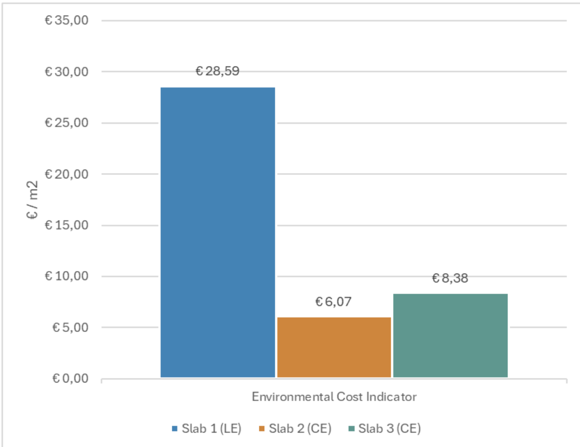
(q) Human Toxicity Potential Carcinogenic



(r) Human Toxicity Potential Non-Carcinogenic



(s) Potential Soil Quality Index



(t) Environmental Cost Indicator

Figure I.3: Environmental Impact over Three Life Cycles for Set A2