Future-Proofing Residential Buildings: Designing for Longevity and Adaptability

Master Thesis

E. Veseli

Final Version

April, 2025

Title	Future-Proofing Residential Buildings: Designing for Longevity and Adaptability
Subtitle	Designing Load-Bearing Structures to Minimize Demolition
Date	April, 2025
Author	Edon Veseli
Student ID	2049902
University	Eindhoven University of Technology
Department	Built Environment
Master	Construction Management and Engineering
Graduation Committee	B. Tunçer W. H. van Dijk F. Schaap

Summary

Introduction

The construction sector in the Netherlands has a significant contribution to its environmental footprint, accounting for approximately 35% of the total CO_2 emissions in the country and 40% of waste. In order to support national climate targets, emissions from the construction sector must be reduced. The most effective way to do this is to reduce the need for new construction materials. Rather than concentrating on recyclability or material innovation, this thesis emphasizes the importance of increasing building longevity.

Research has indicated that buildings constructed after 1990 are demolished at surprisingly high rates. In order to reduce emissions and facilitate a circular economy, modern buildings have to be designed to last in terms of structural integrity, but also in terms of usefulness and relevance across generations. This thesis investigates how the load-bearing structure of mid-rise residential buildings can be designed in a way that enables future-proofing to minimize premature demolition through supporting long-term adaptability.

Literature Study

Modern buildings are frequently demolished due to physical, functional, or economic obsolescence. This happens once services become outdated, or reconstruction projects become more profitable. When buildings are no longer compatible with current user needs, redevelopment is often financially appetizing. To prevent premature demolition, buildings need to be designed to evolve over time.

The Stewart Brand model is used for understanding how buildings support change over time. The framework divides a building into separate layers which change at different rates. This thesis focuses on the layers of structure, space plan, services and skin. These principles very closely align with the open building philosophy, whereby support and infill are considered separately, with the supports being permanent and the infill temporary.

The load-bearing structure is designed to last the longest, and in the case of reinforced concrete, studies have indicated that, if properly maintained, it could last up to 500 years. Historical examples like the Colosseum and St. Peter's Basilica show how well-maintained designs can survive for centuries. The structure layer has to be designed in a way that allows for independent replacement of other layers. Space plans should be flexible enough to accommodate shifting sizes, and services should be separated from the structure.

Methodology

The methodology combines qualitative and quantitative evaluations of various structural configurations and service options to examine the extent to which they can support long-term adaptability. Initially, a quantitative configuration analysis is performed based on four different configurations. These configurations are analysed for their capacity to accommodate various apartment layouts over time. They are evaluated based on three criteria: open floor plan, façade flexibility, and architectural ceiling freedom. Combined, these metrics can be used to track how well the structural system can adapt to new layouts. The most flexible configuration is one that is supported by a core with columns as support and a two-way bearing slab without beams or load-bearing interior walls.

The environmental performance of different MEP options is considered with the help of a Life Cycle Assessment (LCA) using OneClickLCA. The analysis covers a cradle-to-grave approach and models reconfiguration of the floor plan every 12.5 years to model long term adaptability. Each option corresponds to a varying level of flexibility, which translates to different building lifespans based on the service design. In line with addressing the uncertainty in MEP durability, three scenarios are modelled: the worst-case (high frequency of failure), mid-case (average system performance) and best case (overperformance of systems). The outcome demonstrates that out-of-slab options minimize the amount of demolition required for refurbishments. These options result, on average, in a 61% reduction in annual embodied carbon emissions, showcasing the environmental benefit of designing with service accessibility.

A Life Cycle Costing (LCC) analysis is performed to evaluate the financial performance of alternative MEP options within a 300-year time period. The model includes periodic refurbishment costs every 12.5 years, representing the long-term financial requirements of adaptability. Out-of-slab solutions have higher initial construction costs, but become cost-effective over time as they have easier service access. The number of reconstruction cycles is found to be a critical determinant for high costs over time for systems that limit adaptability.

Conclusion

By adopting out-of-slab MEP solutions, buildings can reduce embodied carbon and long-term costs. Designing flexible buildings is beneficial for developers to future-proof their assets, but also achieve advantages in tenders and comply with Paris-proof construction targets. It is recommended for policymakers to include more adaptable principles in revision of regulations such as the *Bouwbesluit*. Future research should investigate the role of alternative low-carbon materials in reducing embodied emissions even further. Moreover, flexibility on the component level, practically on internal partitions, can be explored further in order to improve building lifespans.

Samenvatting

Introductie

De bouwsector in Nederland levert een aanzienlijke bijdrage aan de milieu-impact en is verantwoordelijk voor ongeveer 35% van de totale CO_2-uitstoot in het land en 40% van het afval. Om de nationale klimaatdoelstellingen te ondersteunen, moet de uitstoot van de bouwsector worden verminderd. De meest effectieve manier om dit te doen is door de productie van nieuw bouwmateriaal te verminderen. In plaats van te focussen op recycling of materiaalinnovatie, richt dit onderzoek zich op het verlengen van de levensduur van gebouwen als strategie om de milieu-impact structureel te verlagen.

Onderzoek heeft aangetoond dat gebouwen die na 1990 zijn gebouwd, verrassend snel worden gesloopt. Om emissies te verminderen, moeten moderne gebouwen worden ontworpen om lang mee te gaan op het gebied van structurele integriteit, maar ook qua bruikbaarheid. In deze studie wordt onderzocht hoe de draagconstructie van woongebouwen toekomstbestending kan worden ontworpen om vroegtijdige sloop te minimaliseren door flexibiliteit op de lange termijn te ondersteunen.

Literatuurstudie

Moderne gebouwen worden gesloopt omdat ze fysiek, functioneel of economisch verouderd zijn. Wanneer renovatie een duurdere opgave blijkt te zijn dan de sloop van een gebouw, is herontwikkeling een aantrekkelijke optie. Gebouwen moeten worden ontworpen om vroegtijdige sloop te voorkomen en te reageren op de veranderingen in de behoeften van gebruikers.

Het Stewart Brand model is gebruikt om te begrijpen hoe gebouwen kunnen veranderen. Het model deelt een gebouw in verschillende lagen met elk een eigen levensduur. De belangrijkste lagen zijn: structuur, plattegrond, installaties en gevel. Deze uitgangspunten sluiten aan bij de ‘open building’ filosofie, waarbij de draagconstructie en invulling apart worden beschouwd.

De draagstructuur is gebouwd om het langst mee te gaan. Gewapend betonnen constructies kunnen, mits goed onderhouden, tot wel 500 jaar mee gaan. Er zijn genoeg gebouwen zoals het Colosseum en de Sint-Pietersbasiliek die aantonen na eeuwen nog steeds functioneel te zijn. De draagstructuur moet zodanig worden ontworpen dat de overige drie onafhankelijk lagen kunnen worden vervangen. De plattegrond moet worden aangepast aan flexibelere appartementengroottes en de installaties moeten los van de draagstructuur worden geïnstalleerd.

Onderzoeksmethode

De onderzoeksmethode combineert kwalitatieve en kwantitatieve methoden van verschillende structurele configuraties en installatie-opties. Het doel is om te bepalen in hoeverre de installaties flexibiliteit op de lange termijn bieden. De methode begint met een kwantitatieve analyse van vier verschillende draagstructuurconfiguraties. Deze configuraties zijn beoordeeld op hun vermogen om verschillende appartementengroottes te ondersteunen. Ze zijn geëvalueerd op drie criteria: open plattegrond, flexibiliteit van de gevel en flexibiliteit van het plafond. De meest flexibele configuratie bestaat uit een kern met kolommen en een in twee-richtingen dragende vloer zonder balken of dragende binnenmuren.

Vervolgens zijn de milieuprestaties van verschillende MEP-opties beoordeeld via een levenscyclusanalyse in OneClickLCA. Hierbij wordt de appartementenindeling elke 12,5 jaar gewijzigd om de flexibiliteit op lange termijn te modelleren. Elke optie heeft een verschillende levensduur in verband met het ontwerp van de technische installaties. Om resultaten meer valide te maken zijn drie scenario's gemodelleerd: het worst-case (regelmatige defecten van installaties), mid-case (gemiddelde installatieprestatie) en best-case (over-prestatie van installaties). Opties waarbij installaties buiten de vloer zijn ontworpen resulteren gemiddeld in 61% minder jaarlijkse koolstofemissies. De LCA toont het milieuvoordeel van ontwerpen met toegankelijke installaties.

Een levenscycluskostenanalyse (LCC) is uitgevoerd om de financiële prestaties van alternatieve MEP-opties over een tijdsperiode van 300 jaar te evalueren. Het model omvat periodieke herindelingskosten om de 12,5 jaar, wat de financiële impact van langdurige flexibiliteit impliceert. Ontwerpen met installaties buiten de vloer zijn duurder, maar na verloop van tijd worden ze kosteneffectief, aangezien ze voordelen bieden op het gebied van herindeling en onderhoud. Een hoger aantal reconstructiecycli leidt tot oplopende kosten, waardoor minder flexibele systemen uiteindelijk minder kosteneffectief blijken.

Conclusie

Door gebruik te maken van MEP-opties buiten de vloer kunnen CO_2-emissies en kosten op lange termijn worden verlaagd. Het ontwerpen van flexibele gebouwen is een positieve manier voor ontwikkelaars om hun gebouwen toekomstbestendig te maken, maar ook om voordelen te behalen bij aanbestedingen en te voldoen aan de Paris-proof bouwdoelstellingen. Er kan overwogen worden om beleidsregels zoals het Bouwbesluit te herzien, om flexibele gebouwen mogelijk te maken. Toekomstig onderzoek zou de rol van alternatieve koolstofarme materialen kunnen overwegen, om zo de emissie van gebouwen verder te verminderen. Tevens zou flexibiliteit op componentniveau, zoals scheidingswanden, verder onderzocht kunnen worden, om de gebouwlevensduur te optimaliseren.

Abstract

The construction industry contributes to 35% of the Netherlands' CO_2 emissions and constitutes 40% of the waste produced. To meet climate goals and reduce embodied carbon, the desire for new material production needs to decrease. This thesis does not address recyclability or reuse strategies, but rather seeks to prolong the life of the building through progressive design. Although reinforced concrete can last up to 500 years when properly maintained, buildings are often demolished much sooner, for reasons including physical, functional, or economic obsolescence. Such limitations hinder buildings from evolving with dynamic user needs, compelling the premature demolition of components that are structurally sound. This study investigates a design strategy that accommodates long-term flexibility for mid-rise residential buildings. This study is based on the Stewart Brand model and open building philosophy through different layers of the building. Access to services, adaptable apartment configurations, and decoupling short- and long-lived building layers are fundamental requirements. Four structural configurations are evaluated with regard to spatial flexibility, façade adaptability, and architectural ceiling freedom. The most effective configuration is a column-supported core structure with a two-way spanning slab and no internal load-bearing walls or beams. According to LCA results, out-of-slab MEP options reduce average annual embodied carbon by 61 percent. The LCC shows upfront costs are higher for future-proof MEP options, however, these pay off over a 300-year time period because of fewer reconstruction cycles. According to the study, adaptability will help meet Paris-proof goals while also creating benefits for future tenders, alongside lower long-term costs.

Glossary table

Term	Explanation
Renovation	Repairs or upgrades carried out to restore damaged or outdated building components
Refurbishment	Reconfiguration of internal spaces or systems (new apartment sizes) to meet new functional
MEP	Mechanical, electrical, and plumbing systems
Configuration	A specific structural design of the load-bearing structure, designed to support varying levels of adaptability
Option	One of the five MEP infrastructure strategies tested within a given structural configuration.
LCA (Life Cycle Assessment)	A method for quantifying the environmental impact of MEP options over its full lifespan, executed with OneClickLCA software
LCC (Life Cycle Costing)	A method used to quantify the total cost of MEP options across its lifecycle over a 300 year period
Module	A standardized phase in LCA methodology (A = production + construction, B = use, C = end-of-life)
Scenario	A modelled case representing uncertainty in lifespan assumptions (defined as worst-case, mid-case, or best-case)
Cycle	Periodic reconfigurations of the apartment layout every 12.5 years.

Table of Contents

1. Introduction 1
    1.1 Research problem 1
    1.2 Scope 1
    1.3 Research Question and Subquestions 2
    1.4 Vision 2
    1.5 Relevance 3
    1.6 Reading Guide 4
2. Literature Study 5
    2.1 Environmental Targets 5
    2.2 Demolition as a Problem 6
    2.3 Causes for Demolition 7
    2.4 Preventing Demolition 9
        2.4.1 The Objective 9
        2.4.2 Stewart Brand Model 9
        2.4.3 Open Building 10
        2.4.4 The Strategy 12
    2.5 Requirements per Building Layer 13
        2.5.1 Structure 13
        2.5.2 Space Plan 17
        2.5.3 Services 19
        2.5.4 Skin 21
    2.6 Overview 23
3. Methodology 24
    3.1 Qualitative Assessment 26
        3.1.1 Introduction 26
        3.1.2 Design Framework 26
        3.1.3 Design Configurations 30
            Configuration 1 30
            Configuration 2 32
            Configuration 3 33
            Configuration 4 34
        3.1.4 Summary 35
    3.2 Life Cycle Assessment 36
        3.2.1 Introduction 36
        3.2.2 Evaluation Framework and Methodology 39
        3.2.3 Options 42
            Option 1 43
            Option 2 45

Option 3 47
Option 4 49
3.2.4 Scenario Modelling LCA 54
3.2.5 Environmental Impact 55
3.3 Life Cycle Cost Analysis 58
3.3.1. Benefits 58
3.3.2 LCC Modules 60
Module A: Construction Costs 60
Module B: Refurbishment Costs 61
Module C: End-of Life Costs 65
3.3.3 Inflation 68
3.4 Expansion 70
3.4.1 Floor-to-Building Level Analysis 70
3.4.2 Vertical Expansion 72
3.4.3 Horizontal Expansion 73
3.5 Results and Discussion 75
3.5.1 Results Quantitative Analysis 75
3.5.2 Results LCA 76
3.5.3 Results LCC 77
3.5.4 Discussion 78
3.6 Limitations 80
4. Conclusion and Recommendations 82
4.1 Scientific Relevance 82
4.2 Societal Relevance and Practical Implications 83
4.3 Recommendation for Future Studies 84
Appendices 85
Appendix A: Space Plan Variations 85
Appendix B: Material Impact Option 1 + 2 86
Appendix C: Material Impact Option 3 87
Appendix D: Material Impact Option 4 88
Appendix E: Material Impact Option 5 89
Appendix F: Worst Case LCA 90
Appendix G: Mid case LCA 91
Appendix H: Best Case LCA 92
Appendix I: Module A + B LCC 93
Appendix J: Worst Case LCC 94
Appendix K: Mid Case LCC 95
Appendix L: Best Case LCC 96
Literature 97

List of Figures

Figure 2.1: Circular Economy Strategies (Rijksoverheid, 2023) 5
Figure 2.2: The Waste Hierarchy Pyramid (Zhang et al., 2022) 5
Figure 2.3: Carbon savings of different design strategies (OneClickLCA, 2023) 6
Figure 2.4: Lifespan of different Building Layers in Stewart Brand Model (Arcadis, 2021) 10
Figure 2.5: Evolution of Future-Proof Building Design (Mlote, Budig, & Cheah, 2024) 11
Figure 2.6: The Colloseum in Rome (Berthold Werner, 2020) 13
Figure 2.7: St. Peter's Basilica in Vatican City (Livio Andronico (2014) 13
Figure 2.8: Case Study Embodied Carbon (OneClickLCA, 2021) 14
Figure 2.9: Rigid Frame Structure (Desai, 2023) 14
Figure 2.10: Shear Wall System (More, Bhumare,&Nagargoje, 2023) 14
Figure 2.11: Tube Structural System (Khadka & Bhattarai, 2018) 15
Figure 2.12: Core-Based System (Kawade, Bangde, & Sawai, 2020.) 15
Figure 2.13: Spatial Adaptability in Response to Urban Development and Vacancy 17
Figure 2.14: MEP inside slab (Pure Plumbing Professionals, n.d.) 20
Figure 2.15: MEP below Slab (Adobe Stock, n.d.) 20
Figure 2.16: Transformation of Fellenoord (EDGE, n.d.) 21
Figure 2.17: Transformation of Westraven (cepezed, n.d.) 22
Figure 3.1: Research Framework 25
Figure 3.2: Core-Based Standard Floor Plan 26
Figure 3.3: Space Plan A 27
Figure 3.4: Space Plan B 27
Figure 3.5: Space Plan C 28
Figure 3.6: Space Plan D 28
Figure 3.7: Overview Load-Bearing Configurations 29
Figure 3.8: Configuration 1 30
Figure 3.9: Spatial Reconfiguration Limitations Configuration 1 30
Figure 3.10: Spatial Reconfiguration Feasibility Configuration 1 31
Figure 3.11: One-Way Slab Configuration 1 31
Figure 3.12: Configuration 2 32
Figure 3.13: One-Way Slab Configuration 2 32
Figure 3.14: Configuration 3 33
Figure 3.15: One-Way Slab Configuration 3 33
Figure 3.16: Configuration 4 34
Figure 3.17: Two-Way Slab Configuration 4 34
Figure 3.18: Life Cycle Stages (Morley, 2023)] 36
Figure 3.19: LCA Life Cycle Modules (Shaun, 2025) 37
Figure 3.20: Cradle-to-Grave Approach (Green Element, n.d.) 38
Figure 3.21: Option 1: Embedded MEP Design 43
Figure 3.22: Option 2: Pre-Integrated MEP Channels 45
Figure 3.23: Option 3: MEP Embedded in Foam Concrete Layer 47
Figure 3.24: Computer Floor (HT Raised Floor, n.d.) 49
Figure 3.25: Option 4: MEP in Raised Floor System 49
Figure 3.26: Matix Module (Geoplast, n.d.) 50
Figure 3.27: Technical Drawings of Raised Floor System (Geoplast, n.d.) 50
Figure 3.28: Pedestal Raised Floor System (Xypedestal, n.d.) 50
Figure 3.29: Option 5: MEP in Suspended Ceiling System 52
Figure 3.30: Comparison of Annual Carbon Emissions 56

Figure 3.31: ECI reduction and Tender Advantage (Ecochain, 2023) 58
Figure 3.32: Cumulative Costs over Time 62
Figure 3.33: Shift from Space Plan C to Space plan D. 63
Figure 3.34: Phased Refurbishment Approach 64
Figure 3.35: Cumulative Costs Worst-Case 66
Figure 3.36: Cumulative Costs Mid-Case 66
Figure 3.37: Cumulative Costs Best-Case 67
Figure 3.38: Core-Based Column Structure – Configuration 4 70
Figure 3.39: Configuration 4 75
Figure 3.40: Comparison of Annual Carbon Emissions 76
Figure A1: Space Plan Layouts 85
Figure B1: Material Quantities Option 1 + 2 86
Figure B2: Environmental Footprint Option 1 + 2 86
Figure C1: Material Quantities Option 3 87
Figure C2: Environmental Footprint Option 3 87
Figure D1: Material Quantities Option 4 88
Figure D2: Environmental Footprint Option 4 88
Figure E1: Material Quantities Option 5 89
Figure E2: Environmental Footprint Option 5 89
Figure F1: Worst Case LCA 90
Figure G1: Mid Case LCA 91
Figure H1: Best Case LCA 92
Figure I1: Costs Module A 93
Figure I2: Costs Module B 93
Figure J1: Worst Case LCC 94
Figure K1: Mid Case LCC 95
Figure L1: Best Case LCC 96

List of Tables

Table 1.1: Relevance of the Study 3
Table 1.2: Overview of Research Structure 4
Table 2.1: Evaluation of Structural Systems 15
Table 2.2: Future-Proof Design Requirements per Building Layer 23
Table 3.1: Structural Characteristics of Configurations 29
Table 3.2: Structural Adaptability Assessment 29
Table 3.3: Overview of OneClickLCA Usage per Lifecycle Module 29
Table 3.4: Annual Emissions Option 1 44
Table 3.5: Annual Emissions – Worst Case 55
Table 3.6: Annual Emissions – Mid Case 55
Table 3.7: Annual Emissions – Best Case 56
Table 3.8: Overview Initial Construction Costs 60
Table 3.9: Refurbishment Costs Assessment Framework 61
Table 3.10: Lifespan Assumption Model 65
Table 3.11: Inflation Effect on Long-Term Costs 68
Table 3.12: Structural Layer Impact Expansion 70
Table 3.13: Total Building Height across MEP options 71
Table 3.14: Annual Emissions Results 76
Table 3.15: LCC Cost Breakdown 77
Table 4.1: Stakeholder Recommendations 83

1. Introduction

1.1 Research problem

The Dutch government has set targets to cut CO_2 emissions from the construction sector in the context of its broader climate ambitions. This, in turn, requires that existing buildings comply with new environmental plans or other sustainability systems. The production of new construction materials leads to high levels of embodied carbon. To support this, expanding a building's lifespan can reduce the need for new material production. However, in many cases expanding a building's lifespan is difficult to achieve, since buildings are not designed in a way which allows for renovation or refurbishment in different building layers.

In the 2020s adaptability has become more important, but is still not widely implemented. Buildings need to adapt to demographic trends and shifting preferences over time. However, the static design of many buildings makes it difficult to respond to these changes. As a result of this rigidity in existing buildings, demolition rates are increasing and many structures become obsolete before reaching their maximum possible lifespan.

Without a shift toward adaptable design principles, buildings will continue to have shortened life spans, which ultimately contradicts the goals of carbon reduction. Thus, buildings need to be designed in such a way that prolongs their lifespan which reduces embodied carbon emissions. Designing with adaptability in mind is essential to the realization of future-proof, low-impact buildings that can be renovated, reconfigured, and upgraded over time, rather than demolished.

1.2 Scope

As of 2024, the Netherlands is facing a large housing deficit, which is about 900,000 homes short. The available supply of land to develop on remains constrained, especially in urban areas where the demand is the highest. Mid-rise buildings, which are more scalable than single family homes, achieve a higher density by building vertically. Building regulations in the Netherlands consider 70 meters the point at which the high-rise regulations begin, which imposes more restrictive fire safety, evacuation, and structural requirements. Given the research focus on adaptability and sustainability, and not on any structural complexities, this research narrows its scope to **mid-rise residential buildings up to 70 meters**.

The diversity in demographic and societal needs outlined in the literature study and methodology is especially important in the case of **rental apartments**. Unit flexibility is key for rental developers weighing the ability to adapt to demographics and optimize occupancy rates. Therefore this study is relevant for rental apartments in mid-rise residential buildings.

1.3 Research Question and Subquestions

This research is conducted to help overcome these challenges by focusing on developing buildings with longer life expectancy. Buildings need to be designed with new visions, allowing them to adapt over time instead of being demolished. It is necessary that buildings are flexible and transformable according to future demands, therefore, the research question of this thesis is as follows:

How can the primary load-bearing structure of mid-rise residential buildings be designed to be both sustainable and future-proof in order to avoid premature demolition?

The scope of this study lies in mid-rise residential buildings up to 70 meters. To answer the research question the following sub questions were answered:

- What are the key factors leading to demolition, and how can adaptability mitigate them?
- How does the lifespan of different building layers relate to the total lifespan of the building?
- How can adaptability in building design help developers respond to future market trends and preferences?
- In what way can the load-bearing structure be designed to allow for future flexibility in interior floor layouts and adaptability in the exterior?
- How can MEP systems in mid-rise buildings be designed to be replaceable and adaptable?
- How does adaptability contribute to lowering the embodied carbon of a building over its lifecycle?
- What are the cost implications of reducing demolition and reconstruction cycles through adaptable design?

1.4 Vision

Modern buildings are often designed with a lifespan of 75 to 100 years, even though many of the materials they are made from could last for centuries. A short-term outlook leads to early demolition, construction waste, and high environmental costs. History has shown that structures that are well-designed and responsibly maintained can last hundreds or even thousands of years. They have survived centuries of use and environmental exposure, demonstrating the durability of construction materials.

This research imagines a future where buildings are designed not only to adapt to changing circumstances, but to last for more than 200 years without needing to be entirely demolished. This study aims to set a new foundation of designing longevity, moving from a static design of the construction to a dynamic design whereby the key components of adaptability and longevity intertwine within a future-proof building.

1.5 Relevance

This study holds important implications for both practical application and academic discussion by addressing some of the most pressing issues of adaptability, longevity, and sustainability faced by residential mid-rise buildings. The results of the research can inform a more robust connection between advanced design approaches and their practical use, specifically helping to better design future-proof, sustainable buildings that can meet the needs of a quickly evolving society and new sustainability goals, as listed in Table 1.1.

Practical
• **Designing buildings to be future-proof**: This research explores how dynamic designs can be integrated into buildings to accommodate changing needs, based on new trends or new utilities in an ever-changing physical landscape. This helps reduce the risk of obsolescence by making sure a building retains its usefulness and relevance over time, preserving its value, and minimizing the need for drastic changes in the future. • **Supporting better design decisions in the early stages:** This study offers insights into how MEP layouts can be selected in a way that improves a building's longevity. By comparing various design options with respect to life cycle assessment (LCA) and life cycle costing (LCC), it helps architects and engineers make realistic, future-oriented decisions right from the start.
Social
• **Flexibility in living spaces**: The capacity to adapt a building to changing family size, preferences, and lifestyles ensures that housing is relevant and functional for people throughout their lives. • **Community stability**: This research helps with community stability by ensuring that people are not displaced (as is often the case when a building is demolished), helping to support social stability as well.
Theoretical / Scientific
• **Advancing knowledge in adaptive design**: This line of research builds theoretical knowledge of structural systems that mediate between adaptability and longevity, therefore enhancing the design framework for a novel class of flexible structures used in mid-rise construction. • **Contributing to sustainability goals by reducing carbon footprint**: The environmental footprint of demolition and new construction is significant, particularly in terms of embodied carbon. This thesis is relevant to sustainability goals as it promotes adaptation instead of demolition, which contributes to material conservation and minimization of waste. It advocates energy-efficient designs that help lower CO_2 emissions over a buildings life cycle.

Table 1.1: Relevance of the Study

1.6 Reading Guide

This report is divided into three chapters using different research designs: literature review, methodology, and recommendations. The literature study is established in the first section, the methodology with cycle-based modelling is presented in the second section, and the conclusions and practical recommendations are provided in the third section, together answering the research question stated at the beginning of this report. Table 1.2 gives an overview of the report with its objectives and research design.

Literature Study *(Desk Research)*	**Methodology** *(Cycle Based LCA and LCC Modelling)*	**Recommendations** *(Analysis of Results)*
Identify Key Challenges: Identify the technical, environmental, and social trade-offs between adaptability and sustainability for future-proof mid-rise buildings. **Define Building Layers:** Identify the building layers and their function, longevity potential to be adapted, and sustainability to be integrated into the design. **Establish design criteria**: The primary purpose is to define design criteria for every layer of a building. **Inform Case Study Design:** Provide empirical data and a theoretical backdrop for guiding the practical aspect of performing the case study.	**Exploring different architectural layouts in Revit:** Designing variations in apartment layouts to assess spatial adaptability. **Quantitative assessment of design configurations:** Investigating different load-bearing structures based on flexibility. **Life Cycle Assessment:** Evaluating the environmental impact of different MEP options over their full building lifespan. **Life Cycle Cost Assessment:** Analysing long-term cost trends between various MEP alternatives over a 300-year period	**Provide Actionable Design Guidelines**: Summarize the findings of the research into actionable design guidance that can be implemented to achieve flexible, adaptable, sustainable mid-rise buildings. **Bridge Theory and Practice**: Generate real-world solutions and bring the theoretical research and the case study results into a context that architects, engineers and developers understand. **Support Long-Term Sustainability and Adaptability**: Provide guidance that enables environmental responsibility combined with cost-effectiveness, whilst ensuring usability and relevance over time.

Table 1.2: Overview of Research Structure

A cycle-based Life Cycle Assessment (LCA) and Life Cycle Cost analysis (LCC) are carried out in an attempt to yield actionable strategies for extending residential building lifespan, whilst simultaneously reducing environmental footprints. Various configurations and options are explored for their impact on embodied carbon over their lifespan. The findings from this research can be used as a foundation for architects, engineers, and developers seeking more flexible, sustainable, future-proof buildings, helping to advance toward sustainability targets.

2. Literature Study

2.1 Environmental Targets

The Dutch government has a number of ambitious targets, including a fully circular economy by 2050, and interim targets for 2030. The national strategy is also connected to the goals of the Paris Agreement, which seeks to reduce greenhouse gas emissions and limit global warming (*Ministry of Foreign Affairs of the Netherlands, 2019*). The transition is driven by the necessity of sustainable development, which involves cutting CO_2 emissions by decreasing raw material usage and limiting waste generation while maintaining the economy's stability (*Copper8 et al., 2024*). The construction sector is a critical component of this transition, since it's responsible for 35% of national carbon emissions and 40% of national waste (*Circle Economy, n.d.).* The National Circular Economy Programme 2023-2030 (*Rijksoverheid, 2023*) provides guidelines on how circularity must be applied across various sectors, construction being one of them. It includes targets to reduce raw materials use by 50% by 2030. Figure 2.1 shows four strategies to reduce environmental impact.

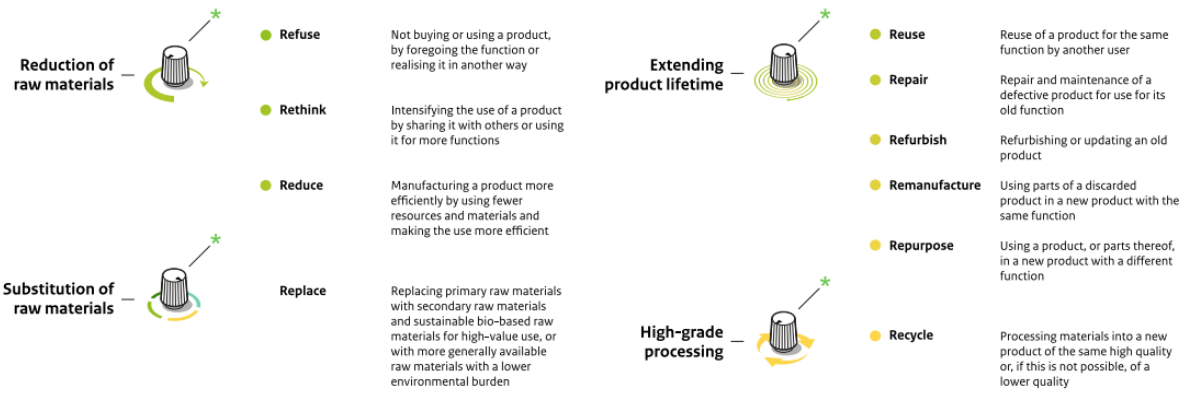

Figure 2.1: Circular Economy Strategies (Rijksoverheid, 2023)

To reduce the environmental impact of materials like concrete and steel, the most effective strategy is to minimize the production of new construction materials. This can be achieved through reusing and recycling construction materials. The Dutch government implements the Waste Hierarchy Framework (*Zhang et al., 2022*). The higher an action in the hierarchy, the greater its environmental benefit. However, recycling and reusing construction components can still help in limiting carbon emissions, investigating a broader approach can improve results. Instead of focusing on single construction components, this thesis focuses on the reuse of a whole building, a strategy which reduces construction waste over the long term.

Figure 2.2: The Waste Hierarchy Pyramid (Zhang et al., 2022)

2.2 Demolition as a Problem

Unlike renovating a building (*Woonbond, 2023*), demolishing one and constructing new buildings is unsustainable. This process requires new raw materials in large amounts, with embodied carbon output much higher than that of renovation. Renovation, on the other hand, involves only partial replacement of one building, and a lot of materials are preserved, so there is less waste from construction. Reusing structures saves the demand for new material production, resulting in lower carbon emissions.

Various design strategies help reduce a building's embodied carbon (*OneClickLCA, 2023*), as depicted in Figure 2.3. This analysis compares what a building with 60-year lifespan emits compared to as 25 year alternative, together with nine different design choices for decreasing total CO_2 output.

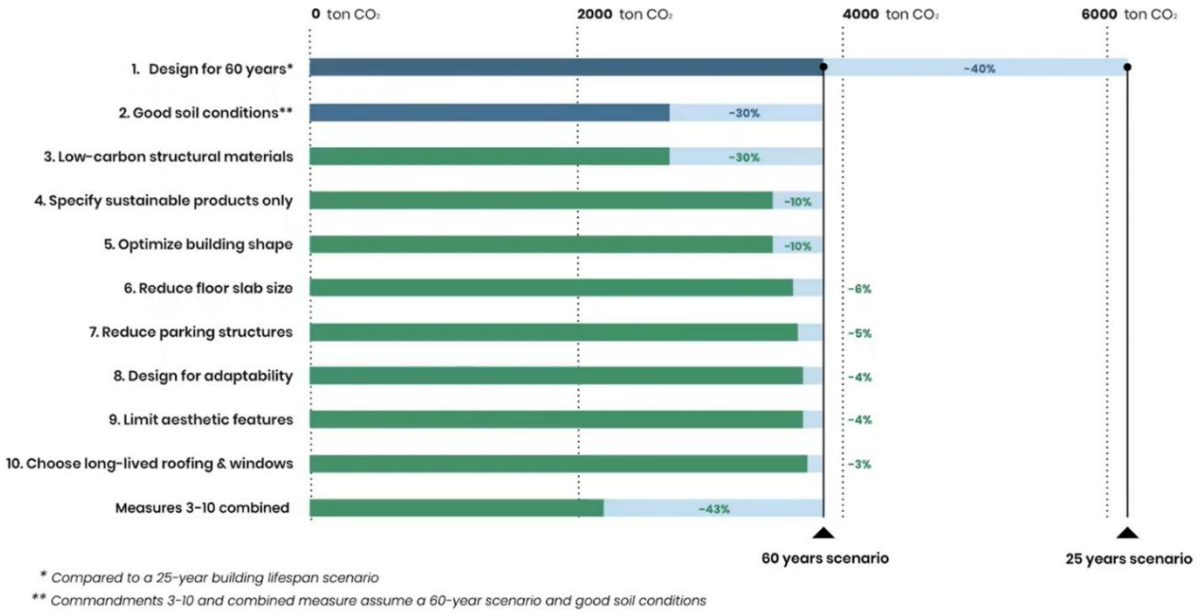

Figure 2.3: Carbon savings of different design strategies (OneClickLCA, 2023)

The biggest drop in carbon emissions comes from extending the lifespan of the building from 25 to 60 years, which results in a 40% decrease in embodied carbon. This thesis aims to expand a building's lifespan even further. Buildings today therefore need to be built with longevity in mind. But actually the reverse is taking place. Despite policy ambitions for circular construction, recent studies indicate that lifespans in multi storey buildings are decreasing. A study (*Andersen & Negendahl, 2023*) investigated patterns of demolition and found that, for modern multi-storey residential buildings, the lifespan is up to 45% shorter than that of buildings constructed before 1990. Even though older buildings were not designed with longevity in mind, their structure has a way better environmental performance since it can remain for a longer period of time. Given the urgency to meet environmental targets, buildings need to represent a vision, where longevity is favoured over short-term efficiency.

2.3 Causes for Demolition

A proper demolition analysis is needed for the design of a future-proof building. By identifying these causes, design strategies can be developed to avoid early demolition. As the waste hierarchy explains, prevention is always better than recovery. Renovation should be considered first to extend the lifespan of a building before considering demolition. Below, three main reasons for demolition are considered, which need to be taken into consideration for the design of this thesis (*Baker et al., 2017; Liu et al., 2014*).

1. *Poor Physical Condition and Obsolescence*

Buildings often get demolished because of structural issues which arise from poor or damaged material quality. Steel reinforcement corrosion, bad concrete mixes, or low load-bearing capacity might cause irreversible structural weakness. Outcomes are often such that it is more cost effective to demolish and rebuild than to repair or reinforce the materials in such structures.

Case: The Pécs apartment complex in Hungary is demolished due to structural issues. Built between 1974 and 1976, this tower was the tallest building in the city and housed more than 800 residents. Structural problems developed over the years as the steel reinforcements used in the concrete components were corroded. Corrosion, primarily induced by moisture and chloride ingress, brought cracking in the concrete and led to a weakening of the building's structural integrity. The cost of repairs to the structure exceeded of the cost of reconstruction. Attempts to rehabilitate the structure were ultimately abandoned. The complex of Pécs was demolished in 2016 (Wikipedia contributors, 2024).

Besides poor material condition, demolition is often the result of outdated plumbing, electrical, heating, and ventilation systems. These critical systems age and become obsolete in terms of efficiency and/or safety. Retrofitting older buildings to improve these services can be costly or technically infeasible, especially when structural alteration is needed. Often, demolition is cheaper, and a new building can be constructed with modern MEP services that comply with current building codes and serves current occupants' needs.

Case: a key example of demolition due to bad services is the St. Louis, Missouri's Pruitt–Igoe housing project, where buildings were demolished due to old MEP infrastructure. Constructed in the 1950s, the complex had failing plumbing, unreliable heating, and inadequate electrical systems resulting in living conditions which were deteriorating. The costs of maintenance were very high, and upgrading the infrastructure became too expensive. The buildings were subsequently demolished later (Shllaku, 2020).

2. *Vacancy - Changing Societal Needs*

With changes in lifestyles, economic conditions, and urban development, housing needs must innovate alongside the evolution of society. Previously functional and efficient buildings may not meet current standards, which can lead to vacancies. As economies develop and households have higher incomes, people want more spacious, better living conditions, which can lead to the vacancy of apartments. Small-scale housing, once viewed as practical for densely populated urban areas, may become undesirable as quality of life expectations change.

Case: In Moscow, an example of dying residential buildings due to changing urban living standards is the Khrushchyovka apartments. These buildings were built in the 1960s to solve a housing crisis, offering affordable and functional shelter for millions of residents. As urban living standards evolved, these compact units within a small square footage were no longer suitable for the modern residents, who preferred large living areas (Roth, 2017).

3. *Economic and Urban Development Factors*

Where vacancy can lead the demolition of a building, the opposite can also happen. External economic and urban development pressures depict the inverse situation, where a building sits on land so valuable that it does not reach the fullest potential. In these scenarios, demolition is conducted to capitalize on the opportunity to realize greater land value through redevelopment. Even buildings that are structurally sound might be torn down in favour of larger, denser, or more profitable developments. This kind of demolition is particularly common in urban centres or rapidly evolving neighbourhoods, where rising land values create a strong motive to build more dwellings. Local authorities can contribute by providing financial incentives or establishing urban renewal programmes that prioritise new builds over refurbishment.

Case: The Heygate Estate was a large housing estate in London consisting of approximately 1,200 homes, most of which were used for social housing. As part of a wider urban regeneration plan, despite being structurally sound, the apartment complexes were demolished in early 2010. The development potential of the site due to its central location was very high. The land was redeveloped for around 2,500 new homes, including private and affordable units. This case shows that deconstruction of economically and structurally viable buildings can also occur as land values and urban development increase (Desai, 2023).

2.4 Preventing Demolition

2.4.1 The Objective

With the primary causes of demolition addressed, the goal of this research can now be explored in more depth. The first category, physical obsolescence, highlights the importance of designing buildings so that their internal systems are as maintainable, repairable, or replaceable as possible, without significant demolition of the building's structure.

This thesis did not go into any further detail regarding durability considerations in the load-bearing structure, as it is outside the intended scope. It is assumed that the degradation of the material in the load-bearing structure is not the reason for demolishing the building. Studying this topic would involve examining early-stage degradation, compound fatigue, structural health monitoring, and the viability of substitute materials like self-healing concrete. This is a technical topic, and therefore this research focuses only on forms of obsolescence that are tied to MEP (mechanical, electrical, and plumbing) systems, which tend to fail sooner than the load-bearing structure itself and comprise a significant portion of the reasons for early demolition.

The second and third causes, vacancy and urban development, go hand in hand. It is increasingly important for buildings to be adaptable to ever-changing urban social demands. Whether plagued with occupancy issues or buffeted by mounting development pressure, a building capable of change in response to the circumstances can clearly suffer fewer and more avoidable early demolitions.

Hence, this study aims to investigate the potential of deriving the principal load bearing structure in a way that accommodates future spatial and service modifications through the future-proofing of the load bearing structure, without compromising structural performance. This allows buildings to age as well as change, and therefore remain valuable in socioeconomic terms over time, while also ensuring their non-obsolescence and avoiding premature loss of function, which aligns with long-term environmental and societal goals.

2.4.2 Stewart Brand Model

The literature study uses the Stewart Brand model to set the requirements for the methodology. The Stewart Brand model divides a building into seven layers, each having a different lifespan (*Arcadis, 2021)*. Site and social are infinite, they are not considered, since they do not impact the longevity of the building. The stuff layer is also not considered, since this layer does not impact the load-bearing design. The research therefore addresses four levels of the Stewart Brand model, namely structure, space plan, services and skin. Though the focus is on the structure layer, it should be created in such a way to make the layers of space plan, services, and skin simple to adapt.

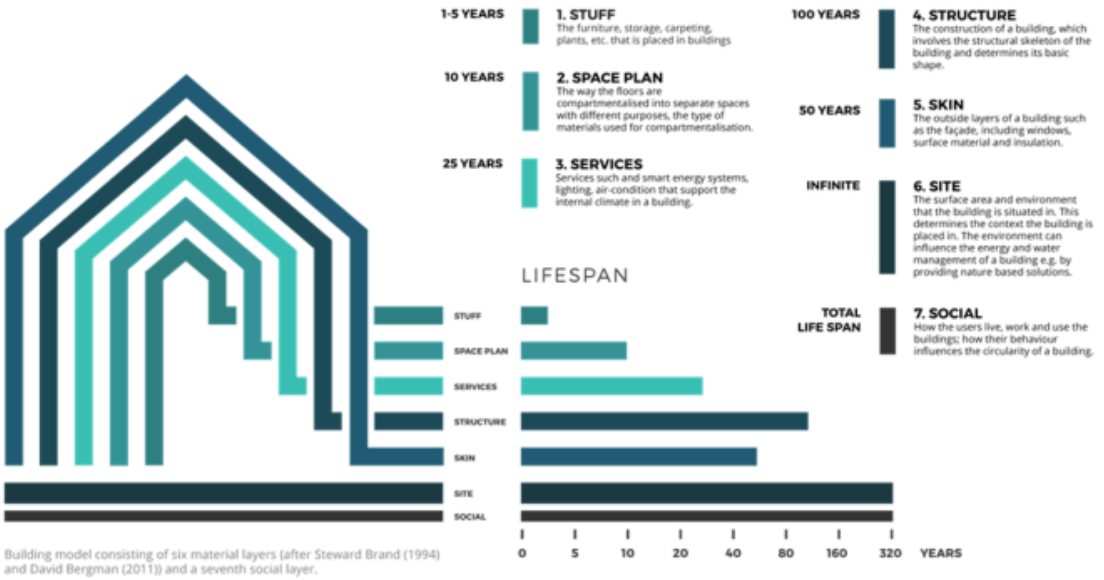

Figure 2.4: Lifespan of different Building Layers in Stewart Brand Model (Arcadis, 2021)

As depicted in Figure 2.4, different layers of a building have different lifespans. While some components can stay the same for an entire century, others need to be repaired or replaced on a regular basis to match functional, technological, or aesthetic shifts. The structure layer has the longest lifespan with, 100 years, while in reality the structure can be used for a longer period.

On the other hand, components such as the space plan, services, and skin have significantly shorter life cycles, which require upgrades or replacements every few decades. These longevity differences illustrate the need for a long-lasting structural system, and therefore answer the second sub question. It shows how the incompatibility of the lifetimes of the layers, particularly of the long-lasting structure and the short-lifespan services, requires a layered design that separates those layers and allows them to be reconfigured in the future without affecting the structure. The remaining part of this study investigates how the building can achieve a 200+ year lifespan for the structure, allowing the building to remain in continuous operation while adapting to the inevitable changes of its other layers.

2.4.3 Open Building

The Stewart Brand model follows an open building philosophy. This is a design philosophy that focuses on creating adaptable buildings that can evolve over time, commonly associated with the Dutch architect John Habraken (*Council on Open Building, n.d*). Its focus on layering, or decomposition of a building into those components with different life cycles of design, construction, and operation allows for flexibility and customization while maintaining sustainability in the long term. Habraken has suggested that there are two major levels in a building, the support level (base building) and the Infill level (fit-out), that can be easily identified, which is comparable to the Stewart Brand model.

This concept allows buildings to adapt to their environment according to their needs, unlike traditional architecture, which leans towards predetermined environments and spaces. This reconfiguration is made possible by the separation of layers of the building, enabling modification of layout, function, or systems, without interference with the core structure. Open building minimizes waste and costs associated with renovation, and improves sustainability. This concept aims to answer two key questions:

1. *How do we design (as well as regulate, fund and manage) a coherent and resilient urban fabric, when individual building projects are initiated by independent actors and will change over time?*

2. *How do we design (and regulate, fund and manage) buildings when decisions about uses and their floor plans are not known, and are usually decided by someone other than the building's architect, and will inevitably change?*

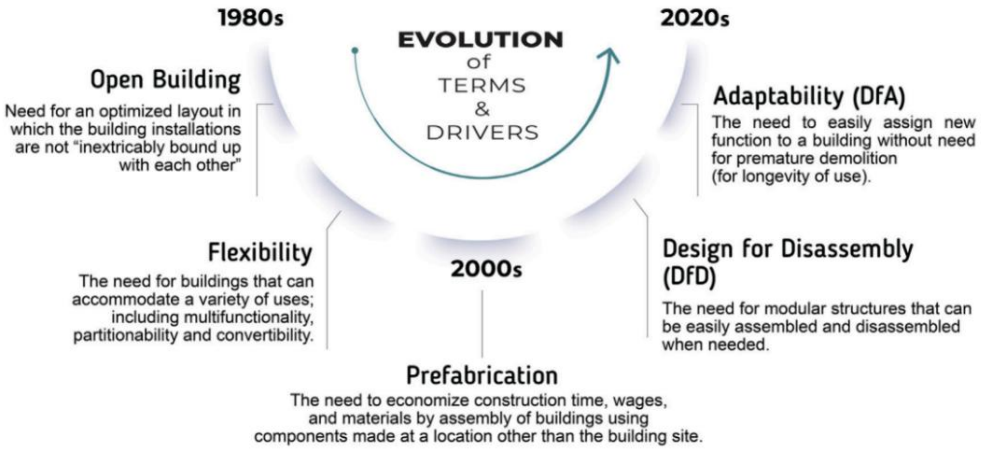

Figure 2.5: Evolution of Future-Proof Building Design (Mlote, Budig, & Cheah, 2024)

Figure 2.5 shows the evolution of building design (*Mlote, Budig, & Cheah, 2024*). The open building movement was founded in the 1980s in reaction to the inflexible and static nature of traditional construction. This led to the principle that buildings should be designed for change. These insights led to the rise of prefabrication in the early 2000s. Modular construction can be seen as the new normal to speed up construction processes and design for disassembly (DfD) allows for construction elements to be reused adding circularity to the built environment and enabling the minimization of material waste. These approaches focus on the end-of-life stage of buildings through material recycling and reuse.

These strategies are effective in improving the efficiency with which current resources are being used, but they do not offer an answer as to how to keep buildings from becoming obsolete in the first place. Circularity and DfD are generally applied to shorter-lifespan layers, like façades or finishes, not the structure layer, which is the focus of this thesis.

Likewise, BREEAM is a well-established assessment tool used to evaluate the sustainability of buildings, including categories related to durability and adaptability. However, BREEAM is not a design guide but a certification framework, providing the criteria for assessment. It fails to offer a basis for managing change over time, which is critical in preventing demolition.

Today, in the 2020s, a paradigm shift has occurred, where open building philosophy now morphed to a more encompassing approach on adaptability (*Russell & Moffatt, 2001*). Through the adoption of adaptive technologies, this research opposes the goal of an ideal building, not by embracing disassembly or recyclability, but by promoting a building with an expanded design that evolves over time. Instead, the objective is not simply cutting down on demolition waste, but eliminating the need for demolition by designing a structure that can adapt and serve multiple generations of use.

2.4.4 The Strategy

In the face of increasing urbanization, changing social demands, and rapid technological advances, buildings need to be able to adapt to changing needs over their lifetime without major renovations or demolition. Adaptability should be a baseline design approach that enables buildings to be future-proof.

Multiple designs have been investigated within both the economic and environmental domains, aiming to convince architects and other stakeholders to design with a more future-proof vision. By focusing on the concept of different building layers, this thesis responds to the two main questions of the open building philosophy.

Incorporating carbon calculations and economic metrics into the open building framework helps ensure designs support long-term adaptability with minimal impact on the environment. This combination improves the concept, so it is more relevant and better able to face the combined issues of climate change and scarcity of resources. This kind of transition is critical for ensuring that buildings are energy-efficient, sustainable, and adaptable to future needs.

Ultimately, when combined, these models underpin the fundamental aim of this research, to create a load bearing structure that promotes internal adaptability and the optimal placement of MEP services in a flexible manner, enhancing the building's capacity to respond to changing societal and functional needs over space and time. Such structures can be adapted for new tenants or spatial needs, meaning they are significantly less likely to be demolished. Thus, the first sub question is answered by showing that the main factors that drive demolition physically obsolescence, vacancy and economic pressure, all relate to non-adaptability. The remaining part of the literature study briefly covers each building layer: structure, services, space plan and skin, identifying specific requirements for each layer that support adaptability and future-proof design.

2.5 Requirements per Building Layer

Next, the interplay between the causes of demolition and the building layers is investigated. The study therefore, provides a theoretical basis for linking requirements to specific layers of buildings, while also assessing how specific configurations can affect environmental performance. The building layer requirements of this study provide the basis for the design, which is created in the methodology section.

2.5.1 Structure

Material

According to the Stewart Brand building layers, it is expected that the structure can last about 100 years. But in practice, reinforced concrete structures, when well-maintained, should last longer. A study found that concrete, with low-permeability, sufficient concrete cover, and proper maintenance can have a service life of 500 years (*Clifton & Knab, 1989*). This shows that the material, if properly designed and maintained should not be the reason to demolish the structure.

As mentioned earlier, this thesis is not concerned with material optimisation. The load-bearing structure is expected to stand for centuries using reinforced concrete as the main material. Stone itself, is already known to last centuries. This is supported by historical examples (*Meva USA, n.d.)* like the Colosseum in Rome, which has endured for almost 2,000 years through natural disasters, wars, and repurposing. Likewise, St. Peter's Basilica in Vatican City, finished in 1626, is still structurally in place and in active use close to 400 years later. These buildings show that, structural systems can well outlast traditional lifespan expectations. While none of these are made from reinforced concrete, they still exhibit the long-term potential of massive structural systems. As modern reinforced concrete should be expected to last well up to 500 years given the right design and maintenance, these examples contribute to confirming the assumption that a service life of multiple centuries is indeed possible.

Figure 2.6: The Colloseum in Rome (Berthold Werner, 2020)

Figure 2.7: St. Peter's Basilica in Vatican City (Livio Andronico (2014)

Figure 2.8 shows a case study (*OneClickLCA, 2023)* where the total embodied carbon of a building is displayed. From this, it can be concluded that the structure itself comprises more than half of a building's total embodied carbon emissions. Demolishing and replacing a building early means wasting the most carbon-intensive component of the building. This underscores the influence of the structure on the environmental performance of buildings and emphasises the need for extending its service life as a main response in mitigating total emissions.

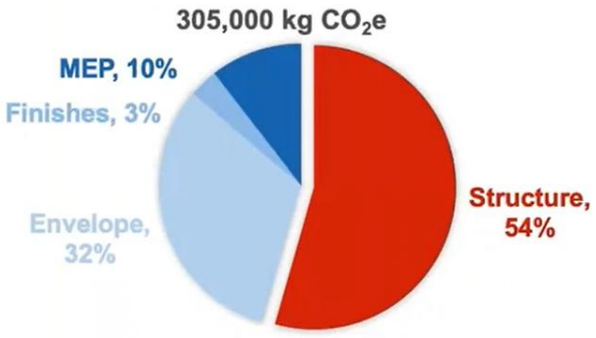

Figure 2.8: Case Study Embodied Carbon (OneClickLCA, 2021)

Type

The main requirement is designing the building for adaptability. This means the structure needs to allow for changes in the interior as well as for the exterior. Below, four different types of load-bearing structures (*Moon, 2018; Patil, 2021*) are briefly explained and displayed with examples. The structural elements highlighted in red represent load-bearing components. These are fixed positions and cannot be moved, therefore limiting adaptability.

Rigid frame structures are made from a network of beams and columns that act as a single unit, allowing the frame to withstand both vertical loads and lateral loads through bending action. This system has been used in mid-rise buildings because of its simplicity. Although this allows for adequate structural support to be maintained through moderate heights, its effectiveness is not suited for lateral forces and ultimately results in loss of structural integrity in taller buildings. To counterbalance these, extra bracing or shear walls need to be implemented to ensure stability.

Figure 2.9: Rigid Frame Structure (Desai, 2023)

The **shear wall system** is built throughout the system of vertically oriented structural walls that are placed in a manner such that lateral forces like wind can be applied. These walls then serve as vertical cantilevers, transferring lateral loads down to the foundation and thus become very effective in mid-rise buildings. Shear walls reduce horizontal displacement significantly more than other types of frame structures, which makes overall stiffness and stability of the building as good as possible. This is effective, however, this type of construction can restrict the architectural flexibility of the building. Shear walls become a fixed part of the façade, therefore possibly limiting its aesthetic appearance.

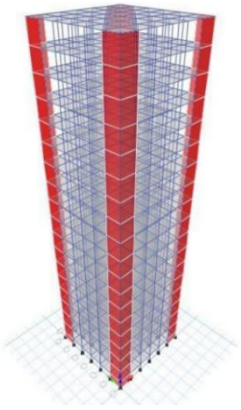

Figure 2.10: Shear Wall System (More, Bhumare,&Nagargoje, 2023)

A tube structural system does not inherently require a core, but it can be combined with one for added stability. The primary load resistance in a tube system comes from the perimeter frame, which acts as a stiff, hollow tube to withstand lateral forces. However, many modern tube structures integrate a central core containing elevators and stairwells to assist with vertical load distribution and further improve stiffness. The example in Figure 2.11 consists of diagonals with distribute the loads to the ground. The tube can also consist of a straight perimeter frame. It is important to note, that also here these fixed elements limit the façade's flexibility.

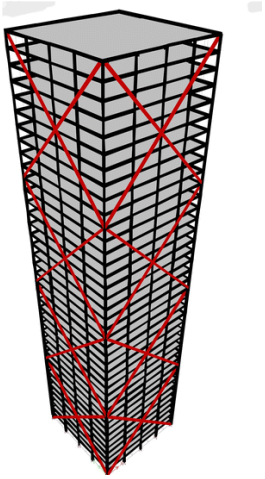

Figure 2.11: Tube Structural System (Khadka & Bhattarai, 2018)

Core-based systems have central cores (usually reinforced concrete structures) as the main-block to resist lateral and vertical forces. This system can take on multiple configurations: core-only (where solely the core stabilizes the building), core + perimeter columns (where exterior columns are used mainly for gravity load support), or core + outriggers (where outrigger walls or trusses are connected to the perimeter columns to enhance stiffness and dampen lateral movement of the structure). Core-based structures are ideal for mid- and high-rise buildings, and flexible floor plans can be achieved. The decision to choose one over the other is based on height, lateral load needs, and the desire for unencumbered open interior spaces.

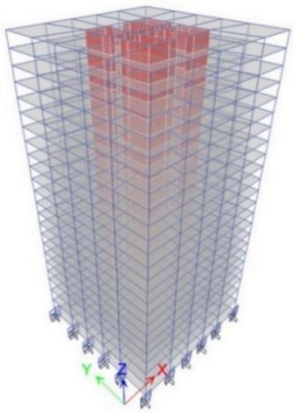

Figure 2.12: Core-Based System (Kawade, Bangde, & Sawai, 2020.)

The Stewart Brand model already introduced the need for adaptive interior layouts and replaceable façades to future-proof buildings. Table 2.1 evaluates the four structure types are based on these two factors, together with heigh suitability. The height can also severely impact the type of structure, therefore making it an important factor for the assessment of the structure type.

Structural System	**Space Plan flexibility**	**Skin Flexibility**	**Height Suitability (20 -70m)**
Rigid Frame System	*High* – Allows for open floor plans	*High* -Allows for façade changes	*Moderate* – requires additional load-bearing elements when adding more floors (hybrid structure)
Shear Wall System	*Low* – Walls restrict layout changes	*Low* – Walls restrict façade changes	*High* – well-suited for mid-rise
Tube Structural System	*High* – Allows for open floor plans	*Low* – Outside columns limit façade modifications	*Moderate* – applicable, but more common for high-rise
Core-Based Structures	*High* – Allows for open floor plans	*High* – Allows for design variations in façade	*High* – ideal for mid-rise

Table 2.1: Evaluation of Structural Systems

From the analysis of structural systems, it can be observed that the core-based structures provide the best combination of the freedom in space planning and skin flexibility along with the height appropriateness for midrise structures (20–70 meters). Core-based structures are very different from shear wall systems and allow for open floor plans without losing structural performance. Furthermore, they offer more design freedom for façades than tube systems, making them suitable for flexible and future-proof construction. Since core-based structures were found to be the best suited, the next step is to optimize their design by selecting structural elements. These core-based structures are evaluated according to which slab type (one-way slab or two-way slab) dominates, and other load bearing elements, such as beams, columns, and load-bearing walls. The methodology section examines this.

2.5.2 Space Plan

The space plan layer should be flexible to suit changing residential requirements over time (*Pelsmakers & Warwick, 2022*), following the Stewart Brand approach, this layer is altered every 10 years. Urban development can lead to more market demand, and suburbanisation can lead to occupant vacancy. The design should accommodate this with flexibility in the apartment sizes. If they can be adapted, the new size can make it more attractive to suit tenants.

Urban development leads to increased demand for housing. A floor plan which initially consisted of three apartments, can be configured into a floor plan consisting of five apartments. Allowing for higher density within the building reduces the chances of demolition due to economic obsolescence. Vacancy is the opposite of this approach. When a building has outdated layouts which are too small, it becomes less attractive to occupants. Therefore, reconfiguring the units into larger apartments can encourage occupants to move in. Figure 2.13 explains these two opposing conditions. This illustrates the third sub question, by demonstrating that a flexible design, at the level of the space plan, grants the developer the option to respond to changing demands.

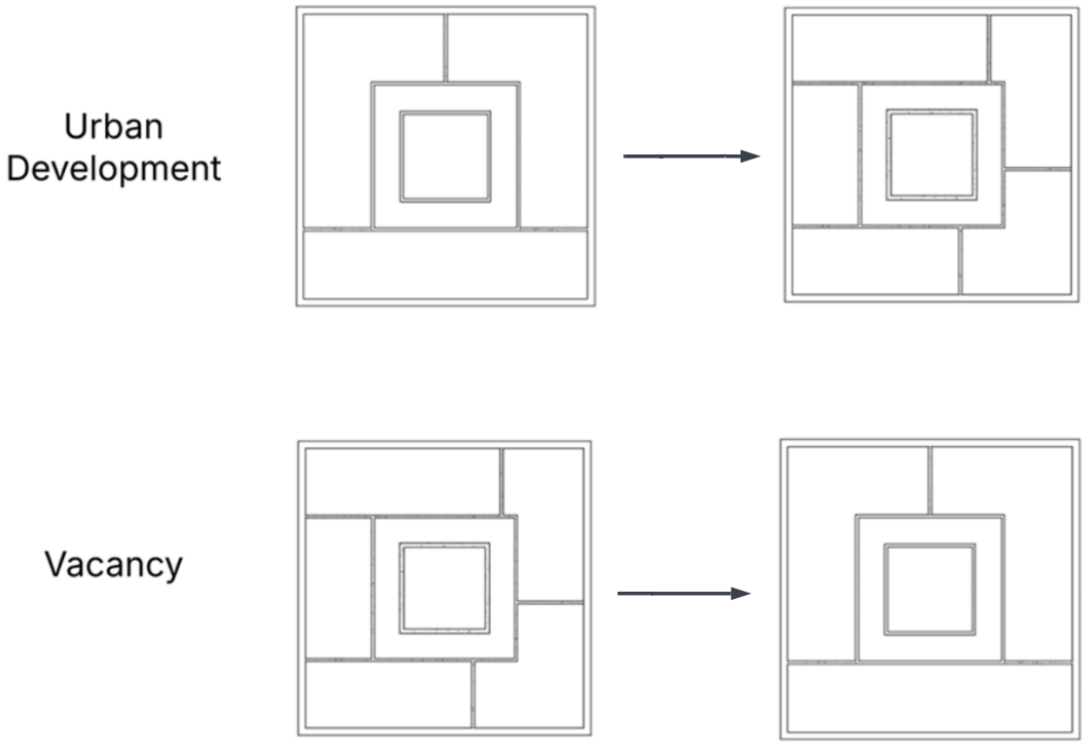

Figure 2.13: Spatial Adaptability in Response to Urban Development and Vacancy

Altering building floor plans should be executed in a way that does not influence the environment negatively. This means reconstructing apartments without generating lots of construction waste and without impacting load-bearing components. Changing apartments' size, means relocating kitchens and bathrooms, as well as the internal partitioning of space, which influences two main building components, elaborated on the next page.

Interior Walls

Changing layouts requires the change of interior walls. The most important requirement is that these walls should not bear any loads from above. If this is the case. demolition of these walls involves a lot of structural risk. The design should therefore be made so it allows for sufficient open space. From the structure section, it became clear that a core structure is chosen for the optimisation of an open floor plan, allowing the structure to provide one big open space. This section helps to reaffirm the importance of this approach.

The core is the central stabilizing element of the building, allowing both vertical and horizontal load bearings to be concentrated in a central location (*Ilgın, 2023*). This construction type should allow interior spaces to be altered if internal load-bearing walls are not required. In the methodology section, different types of core structures are assessed further.

MEP

The change in the number of apartments on the floor, from three to five for example, demands not only spatial reorganization, but a considerable expansion of the technical infrastructure. Every new apartment adds new functional areas like kitchens, bathrooms, and toilets, thus requiring independent plumbing, HVAC ducts. and electrical connections. The higher level of service intensity requires a more sophisticated and distributed MEP distribution across the floor.

Where traditional design does not account for adaptability, accessing and rerouting MEP infrastructure becomes a challenging and invasive task, involving breaking into structural slabs. This results in significant construction waste, increased labour, and disruption to occupants. Therefore, these changes should be made inside the building with minimal material waste and disruption to the building's structure.

In the context of apartment layouts, the term refurbishment is used for its modifying according to new spatial or functional requirements. Renovation, on the other hand, generally means repairing or modernizing areas that are damaged or obsolete in a building. However, both processes must be served by accessible MEP systems, since modifications to any of these functions, due to upgrades or repairs, will typically require alterations to the mechanical, electrical, or plumbing systems.

The strategies of replaceable and upgradeable systems are examined in the next section on services. Keeping MEP systems accessible and adaptable is in line with the principles of both the space plan layer as well as the service layer.

2.5.3 Services

There are multiple reasons why MEP systems need to be replaced over the years (*InnoDez, n.d.)*. Building codes are updated to enhance safety and energy efficiency. Many older buildings are no longer up to today's standards. Improving MEP systems for code compliance is often necessary to meet new sustainability and safety standards.

Fully updated systems are vitally important, as they can reduce safety risks associated with aging electrical and plumbing systems, like fire hazards, leaking pipes, and contamination. Updating with new systems reduces these risks, providing a safer space for occupants.

Besides safety considerations, another key driver is improved energy efficiency. Older systems are less efficient, which leads to greater energy use and higher costs. Modern, energy-efficient HVAC technologies drastically reduce energy, making them the cheaper and more sustainable option. This thesis focuses on reducing embodied carbon, not operational carbon. Any further exploration of these systems is not carried out.

Outdated MEP systems can lead to the demolition of a structure. To assess this further, the service layer is explored below based on its accessibility in traditional construction and its effect on the design of the load-bearing structure.

Accessible Services

MEP systems typically have a lifespan of 20 to 25 years. Most energy-related systems, like heating systems, air conditioning, and ventilation units, are accessible (*GDI Engineering Design, 2023*). These units are not embedded inside the structural system, and therefore do not influence the design or longevity of the building, since maintenance is easily performed. These units are usually placed at a strategic location, allowing for easy replacement.

Inaccessible Services

In traditional structures, MEP systems are integrated inside the slabs, which is one of the most significant problems regarding adaptability. This results in a system that is inflexible, because all modifications to MEP components can only be carried out by breaking the slab.

Following the Stewart Brand model, MEP services are replaced every 25 years. However, this only accounts for MEP units and not for the infrastructure itself. Plumbing pipes typically have a lifespan of about 75 years (*Aztec Plumbing & Drains, n.d*.). New research has indicated that plastic plumbing pipes can even last 100 years (*Pinter, Travnicek, & Arbeiter, 2024*). However, they cannot last up to two or three centuries like the structure layer. Outdated plumbing infrastructure can cause health issues due to contamination. Outdated ventilation infrastructure can cause unhealthy indoor environments with bad air quality. At a certain point, these embedded services need to be removed to improve living conditions.

In the best scenario, plumbing and ventilation infrastructure might reach 100 years. However, failure does occur in these systems due to material degradation and corrosion, which can lead to significant damage to the building. Over time, this can compromise the integrity and the financial viability of the building.

From the space plan section, it has been made clear how crucial adaptability in MEP services is when switching apartment sizes. If apartment layouts need to be modified, repositioning bathrooms and kitchens means rerouting MEP infrastructure.

Horizontal services inside the slab limit the building lifespan. Replacing horizontal MEP systems, because of failure or apartment configuration, can be both costly and complicated in buildings where services have been incorporated into structural elements. Breaking the whole slab is needed to enter these systems, which is highly impractical therefore making demolition of the building a more viable option than retrofitting. Pushing the development of adaptable and accessible MEP solutions offers the potential for longer building lifespans and reduced material waste throughout the required lifetime of the building.

MEP systems should be placed outside of the structural slab and not embedded into it in order to ensure long-term flexibility, as well as to reduce future renovation costs. This design puts MEP infrastructure in accessible areas, which allows for adjustments over time without major disruptions. This approach is common in commercial buildings and residential buildings should implement this approach as well to increase their lifespan. The methodology section explores three options for MEP infrastructure design.

Figure 2.14: MEP inside slab (Pure Plumbing Professionals, n.d.)

Figure 2.15: MEP below Slab (Adobe Stock, n.d.)

2.5.4 Skin

Architectural styles and tastes change over time, and a building that was once modern can end up feeling dated or unattractive. From time to time, any building may need to adjust its skin, as its surroundings and people's preferences for it change. It is clear from literature that outdated skin does not directly cause demolition, however, since its replacement is costly, it can be a subfactor in the decision for demolition or renovation. However, it does need to be taken into consideration to make buildings more future-proof.

Utilization of modular panels is necessary, as replacements or basic aesthetic changes can be carried out without affecting the load-bearing structure. With modular, adaptable façades, building owners can renew the skin while maintaining the load-bearing structure.

To highlight the role of adaptability in the skin layer, two examples are provided below whose façades have undergone a fundamental transformation to fulfil the needs of modernity. These examples are non-residential but still show how adaptively re-used façades can be transformed to meet modern requirements

Fellenoord 15, Eindhoven

Originally built in 1972, the Fellenoord 15 (*EDGE, n.d.*) building in Eindhoven was refitted to bring its façade into the modern era and to make it more energy-efficient. Tasked with replacing the aging exterior, the replacement involved a full façade redesign, resulting in a fresh new glass-fronted skin. These changes feature an aesthetic enhancement of the building. The renovation also highlights how a responsive façade design can help enhance the longevity of a building to satisfy current architectural and sustainability requirements.

Figure 2.16: Transformation of Fellenoord (EDGE, n.d.)

Westraven, Utrecht

The Westraven (cepezed, n.d.) in Utrecht was originally constructed in the 1970s as a government office, but underwent a full renovation to modernize its function and aesthetic. The building was entirely refurbished with a next-generation textile façade system that significantly enhanced the building's performance. Its new façade enhanced insulation and reduced solar heat gain, and therefore energy consumption, while also giving the building a fresh contemporary look. The renovation illustrates how a purposeful facade update can breathe new life into a building, extending its useful life and aligning it with contemporary standards of sustainability and aesthetics with far less environmental and economic waste than demolishing it.

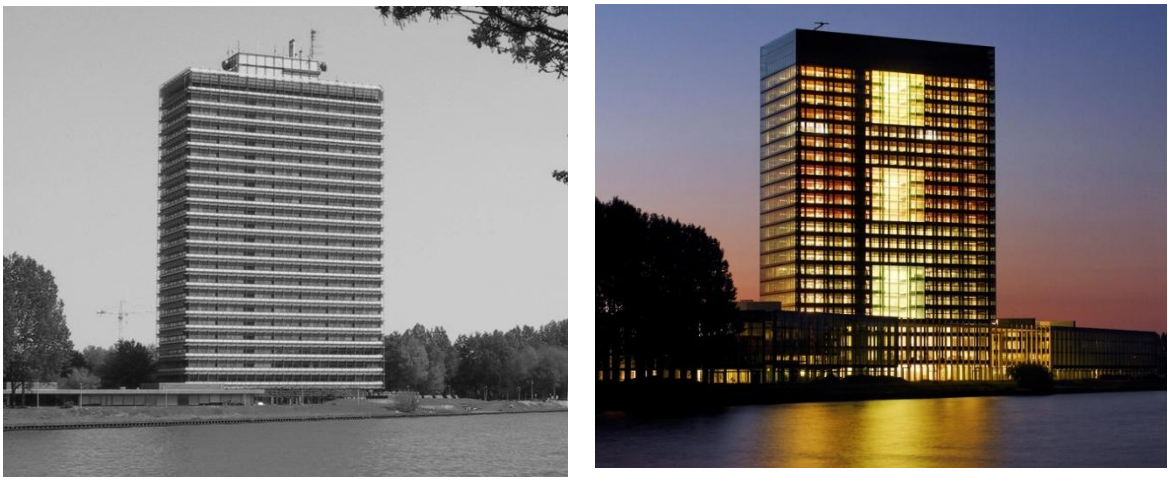

Figure 2.17: Transformation of Westraven (cepezed, n.d.)

The literature review aims to specify design needs for the building that contribute to making it sustainable and future-proof. The skin, meanwhile, is designed as a façade system that can be adapted over time with upgraded or replaced components that need not interfere with the load-bearing structure. The parameters for achieving this involve ensuring that large structural components are not placed at the outside of the building, which restricts the flexibility of the façade. This approach enhances replacement aspects of the building's skin while allowing for the integration of new finishes or style updates, enabling the building to remain visually and functionally relevant through time.

2.6 Overview

Based on the literature review, it is considered that the majority of buildings are demolished because of *changing requirements* and *outdated MEP*. The general requirements for designing future-proof mid-rise buildings include aspects regarding adaptability, longevity, and sustainability. These fundamental principles enable the building to adjust to future trends and needs. All layers have been investigated in the literature study, each resulting in specific design requirements. An overview of the requirements are shown in Table 2.2.

Building Layer	**Impact on environment**	**Future-proof design requirements**
Structure	Largest environmental impact due to early demolition without reaching maximum potential. Lifespan should be expanded by centuries to lower environmental impact from the construction industry.	Core-based structure in reinforced concrete, study shows material has the potential to reach 500 years. Other layers impact early demolition.
Space plan	Buildings need to adapt the space plan to avoid vacancy and respond to urban development trends to avoid demolition.	The structure must maximize open space. Slab type and other structural elements influence the design.
Services	MEP infrastructure embedded inside slabs can lead to structural integrity issues and lead to unhealthy living conditions, which can cause demolition.	MEP systems should be placed outside of slabs to allow for easier rerouting and repair.
Skin	Outdated façades contribute to energy inefficiency (operational carbon) leading to a negative impact on the environment.	The load-bearing structure must allow the skin to be adaptable to improve energy efficiency and aesthetics.

Table 2.2: Future-Proof Design Requirements per Building Layer

The literature study yielded insights into important design criteria for future-proofing a building. The methodology section investigates different load-bearing structures in terms of their adaptability, environmental footprint, and economic impact. This section investigates how minimizing impact can be achieved as layouts change over time through building lifecycle evaluation, potentially looking at the effect of various design configurations on carbon emissions through time.

3. Methodology

The methodology discusses the effects of adaptability and longevity on the environmental and economic performance of load-bearing structures. The methodology builds on the requirements derived from the literature study, using these as a theoretical basis in the assessment of load-bearing configurations and MEP alternatives. The methodology consists of three main components, which are explained below.

The first phase of the study introduces the load-bearing configurations at floor level, answering the fourth sub question. The configurations proposed are first scored with a qualitative assessment based on their openness and flexibility. The configurations are different based on their structural components and therefore differ in their level of openness.

Next, a Life Cycle Assessment (LCA) is carried out to calculate the environmental impacts for various MEP options over their lifespan. The aim of this evaluation is to find the option with the minimal embodied carbon footprint. This analysis uses a systematic methodology to measure embodied carbon emissions and material consumption related to each option over the full life of the option from material extraction and production to use and subsequent demolition. The analysis considers environmental impact over time , including refurbishment cycles, to determine the most sustainable option. For a more accurate, data-driven, and standardized methodology, this analysis is performed using the OneClickLCA software. OneClick LCA creates accurate comparisons between alternative options with each other using material databases and data on environmental impact factors. The reliability of OneClickLCA has been previously demonstrated in academic research, where the software was utilized for the evaluation of embodied carbon for building case studies and the assessment of consistency in LCA results (*Chaudhary, Jahromi, & Keyhani, 2023*).

After the LCA, a Life Cycle Cost (LCC) analysis follows, which assesses the costs over the lifetime of the options based on their lifespan and refurbishment costs. These include both initial construction costs and anticipated future expenditures, providing good insight into the long-term economic viability of all designs over a 300 year lifespan. The study's economics are heavily driven by inflation, since the options are assessed over centuries. Options with shorter life expectancies present greater economic risk, since the material and labour become more expensive over time, which only creates an incentive for costly, short-sighted renovations.

The LCA and LCC analyses look for a trigger (or key driver) for stakeholders to adopt a future-proof way of building design for residential buildings. With a qualitative approach, the different options can be assessed and the most sustainable options can be chosen. The final three sub questions are answered in this part and help evaluate how adaptable design strategies impact embodied carbon over time, and how they influence the long-term costs of reconfiguration. The results of this section help to develop recommendations for more sustainable decision-making in construction over the long run.

Still, it is worth noting that these instances are tested to an extreme, assuming cycles in which space plan changes often, and adaptation is immediate and maximized in order to show the possible benefits. Although this method offers valuable insights, it does not fully capture the reality of construction and refurbishment cycles. To address this gap, the final part of the methodology scales these findings to the whole-building context, exploring more realistic adaptability cycles. The transition from theoretical extreme cases to practical implementation ensures the findings are relevant for architects, developers, and policymakers looking forward to the future of their projects. The full methodology is outlined in Figure 3.1.

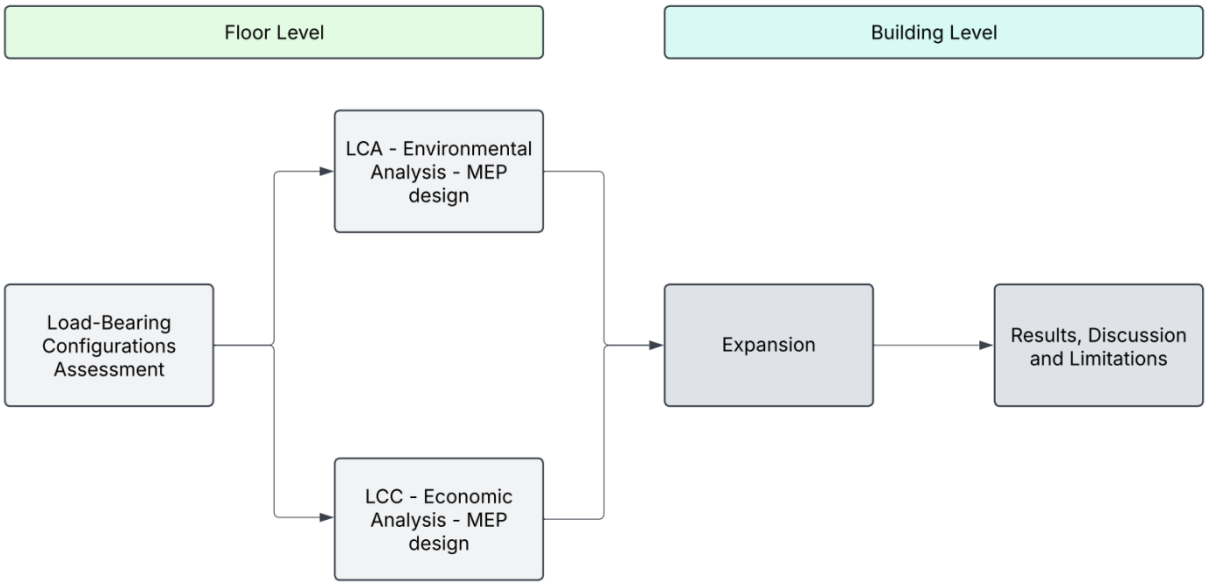

Figure 3.1: Research Framework

3.1 Qualitative Assessment

3.1.1 Introduction

In the first part of the methodology a qualitative assessment is carried out on the primary load-bearing structure of mid-rise residential buildings regarding long-term adaptability and flexibility. The evaluation does not focus on quantitative life cycle analyses but on a qualitative judgement of four structural configurations regarding their ability to accommodate future changes in both the space plan and skin. The assessment is performed according to three primary criteria regarding flexibility:

- *Open floor plan flexibility*: to what extent can the load-bearing configuration accommodate different space plan variations?
- Façade *flexibility*: can the façade be upgraded without interrupting configured apartment layouts?
- *Architectural ceiling freedom*: does the configuration eliminate structural elements to allow for a ceiling that enhances interior aesthetics and future reconfigurations?

3.1.2 Design Framework

All designs work off a standard apartment size and a fixed floor plan. A core-based design is chosen as the structure. The study looks at several load bearing configurations for a typical midrise apartment floor plan with the dimensions of 20 x 20 m comprising 300 m² of usable apartment area surrounding a centrally located 6 × 6 m core, which include stairs and elevator shafts. The hallway has a width of 2 m. The core walls not only constitute some of the primary load-bearing elements of the building, contributing to the general stability of the structure, but also accommodate vertical circulation, MEP services, etc. The walls of the hallway are also load-bearing, since they are not changed throughout the entire life of the building. This part of the structure should not be demolished until the end of the lifespan, they add to the robustness and longevity of the building and ensure structural integrity as the layout of interiors evolves. Four different building configurations, which differ structurally, are assessed. Four different space plan layouts are designed to illustrate how the configurations can accommodate shifting apartment sizes in response to changing needs. The configurations are assessed based on whether they can allow these shifts in different space plan layouts.

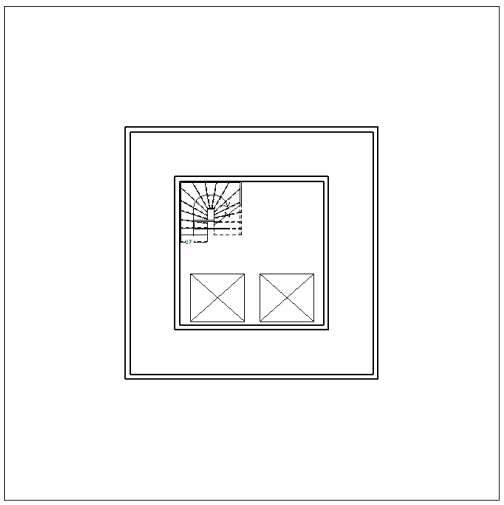

Figure 3.2: Core-Based Standard Floor Plan

Space Plan A

This space plan consists of apartments with a size of 60 m² and has been created to meet the needs of single professionals, couples, or small households. This setup provides a balanced living arrangement with all basic amenities. The 300 m^2 of open space is divided into 5 apartments of approximately 60 m^2.

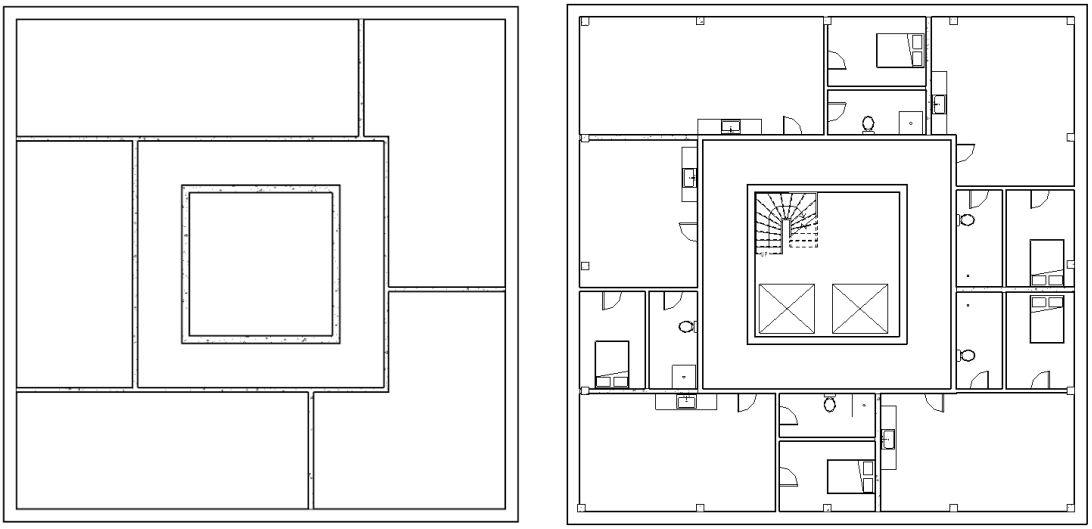

Figure 3.3: Space Plan A

Space Plan B

The next layout presents a situation where, because of rising housing costs, single-family homes become unaffordable, large families move more into apartments instead of houses. Developers can act on this new trend by making apartment sizes larger, since families require more space. Therefore, in the second situation, the layout expands to 100 m². These larger residences meet the needs of expanding families with extra bedrooms, larger kitchens, and ample living areas.

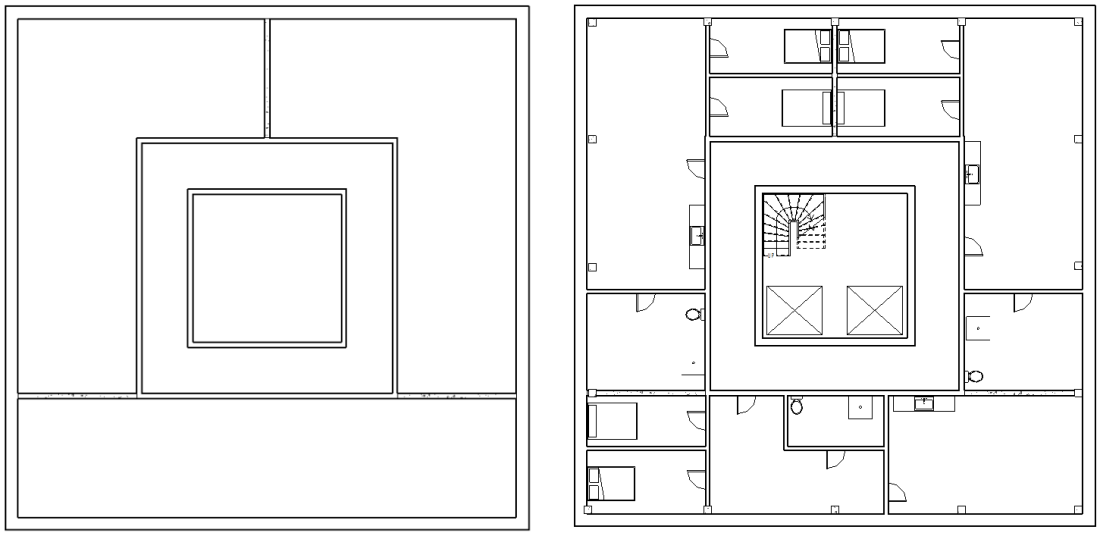

Figure 3.4: Space Plan B

Space Plan C

Layout C addresses the needs of an aging population. In this case, apartments can be converted into smaller units of 50 m², so they are more accessible for older people. The Netherlands is currently facing an aging population. More elderly people live alone due to longer life expectancy and the loss of a partner. Again, developers can act on this new situation by making the apartment sizes of the last layout much smaller. These smaller apartments are easier to maintain and better suited for mobility needs.

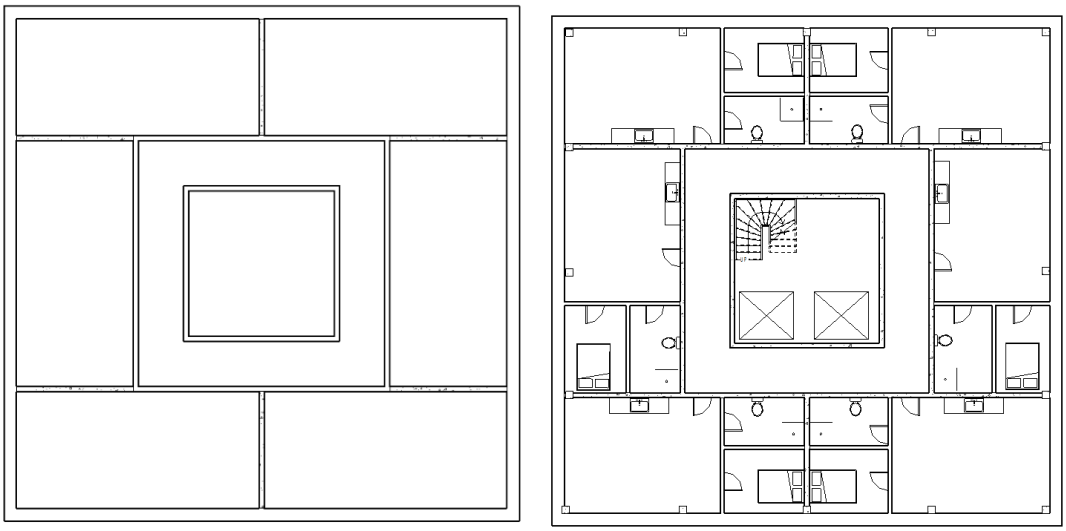

Figure 3.5: Space Plan C

Space Plan D

The last layout takes into account a scarcity of student accommodation, which prompts even more subdivision of apartments into 25 m² micro-units. These layouts offer affordable living conditions, equipped with a kitchen and bathroom. Many student cities in the Netherlands also face a shortage of student homes, making it a very profitable option for developers if they can act on this market opportunity.

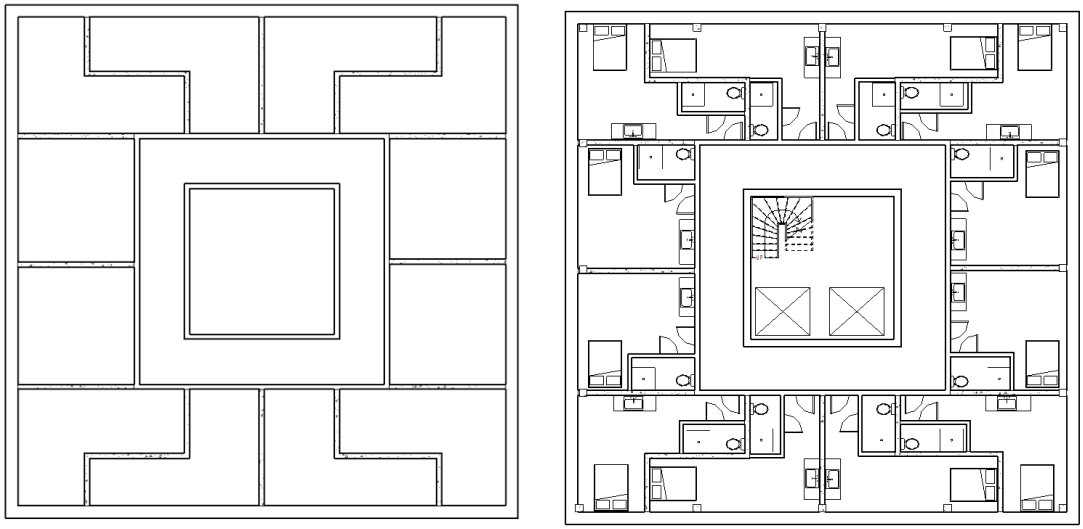

Figure 3.6: Space Plan D

Now with the design framework set, the different load-bearing configurations can be introduced, which differ in structural elements. The configurations differ in the type of slab and in the type of supporting elements below the slab. One-way slab transfers loads to beams or walls along only one direction, which needs more fixed structural elements. In contrast, two-way slab distributes loads in multiple directions. All configurations can be seen below, each numbered to reflect their specific structural components, as shown in Table 3.1.

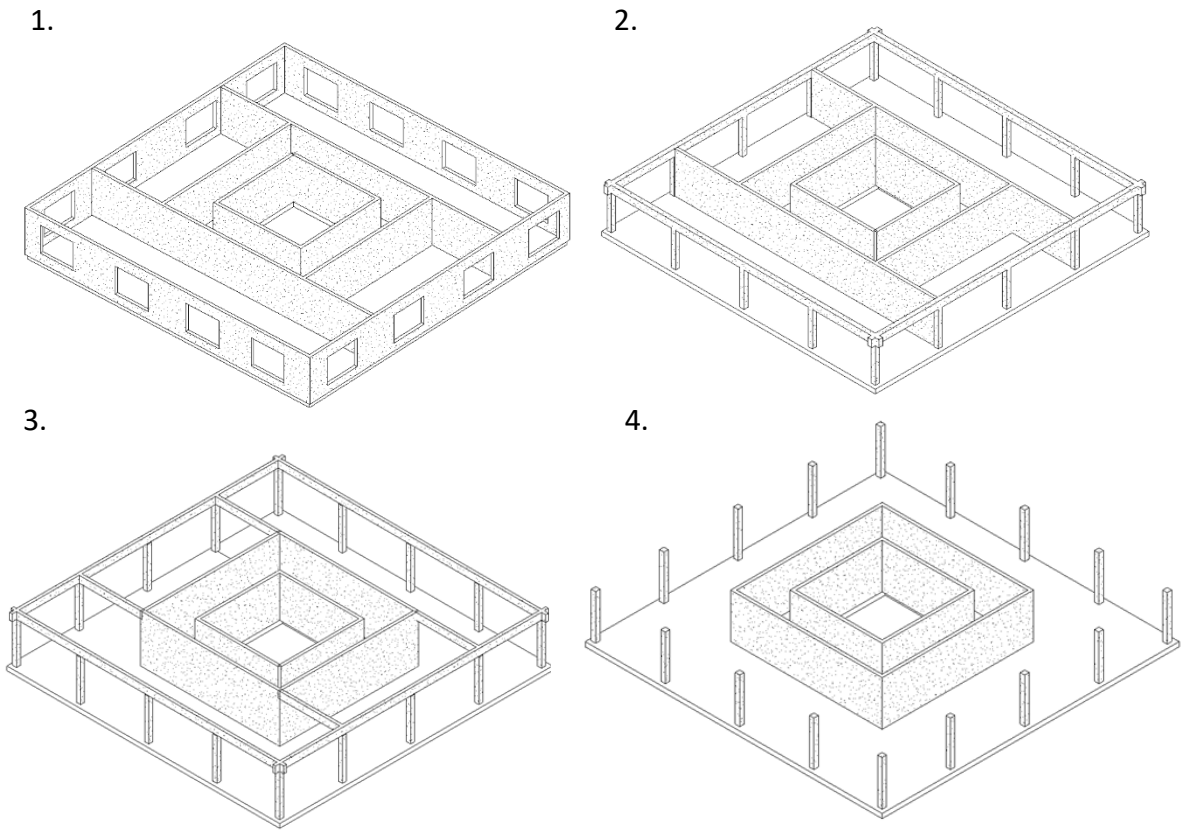

Figure 3.7: Overview Load-Bearing Configurations

The floor slab type, the existence of beams, and the presence of load-bearing walls outside the core differ across the configurations. The aim is to find the structural configuration that provides the best long-term spatial flexibility. Since MEP is not considered yet, the floor-to-ceiling height is fixed at 2.6m. The configurations are elaborated on the next pages. The best performing configuration is adopted in the following stages of the study (i.e., MEP integration strategies via LCA and LCC).

Configuration	**Floor Type**	**Load-Bearing walls (besides core)**	**Beams**
Configuration 1	One Way	Yes	Yes
Configuration 2	One Way	No	Yes
Configuration 3	One way	No	Yes
Configuration 4	Two way	No	No

Table 3.1: Structural Characteristics of Configurations

3.1.3 Design Configurations

Configuration 1

A load-bearing wall structural system without the use of any columns or beams is used to create Configuration 1. This creates a structurally stiff arrangement where the walls themselves are the vertical load-bearing element of the building. As a one-way slab system can transfer loads in one direction only, an increased number of load-bearing walls is required to support the loads coming from the slab.

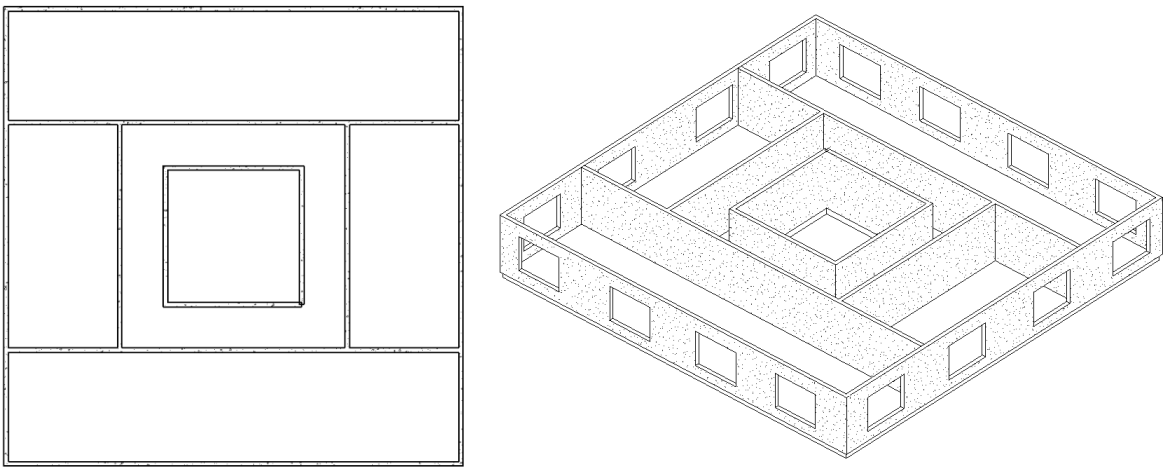

Figure 3.8: Configuration 1

Since the structure relies on load-bearing walls , it severely restricts spatial reconfigurability as this cannot be altered over time. In Figure 3.9 space plan A and space plan B are displayed. The red circles indicate the absence of walls in space plan A and B. To alter these layouts, the walls of the structure need to be demolished. However, this is not possible, since the walls are load-bearing, which leads to structural risk. Retrofitting of such a structure is also very expensive. Open floor plan flexibility is low, since space plan A and space plan B cannot be configured.

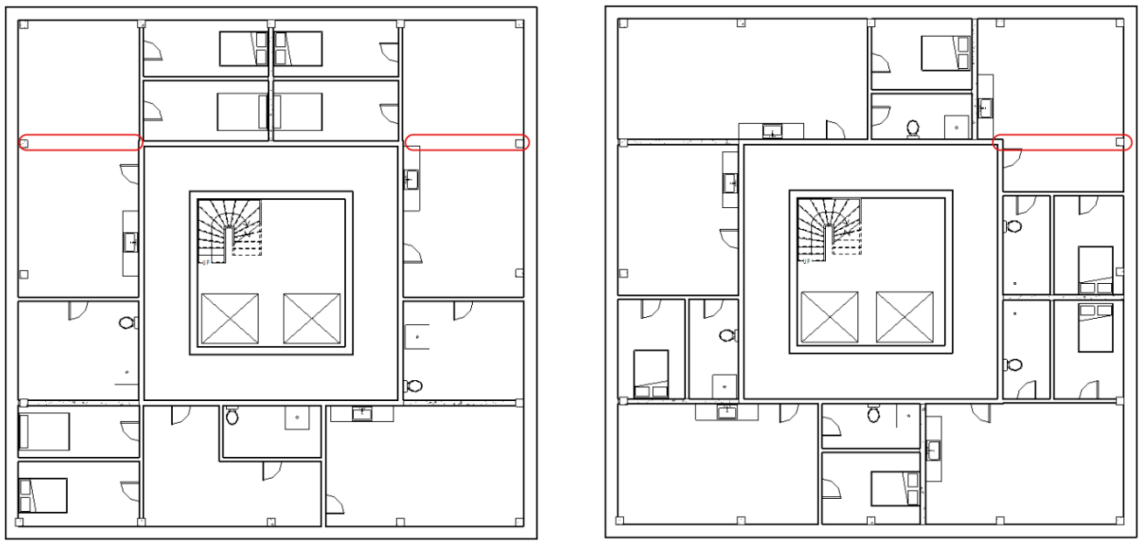

Figure 3.9: Spatial Reconfiguration Limitations Configuration 1

Only floor plans that retain these structural walls in their original positions, indicated in green, are feasible within this configuration.

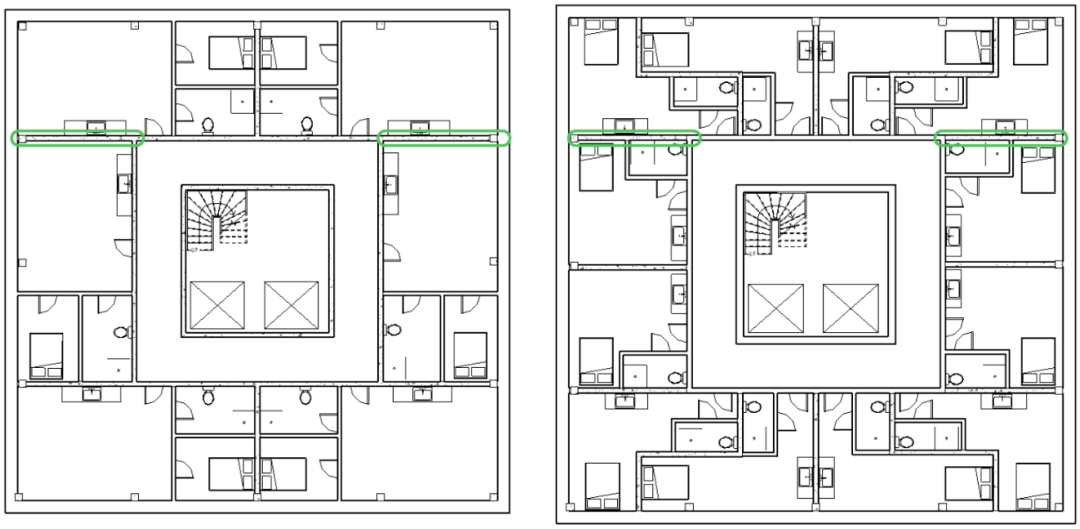

Figure 3.10: Spatial Reconfiguration Feasibility Configuration 1

Secondly, the load-bearing walls along the façade greatly restrict the building's outer flexibility. As these walls are used for stability in the structural system, the position of window openings becomes fixed, and with this, there is little to no flexibility in their change of position in any future redesign of apartments. Unlike the outer cladding or skin of the building, which may be stripped and replaced to provide a more modern façade for the building, the underlying structural walls must remain in place. This means that the façade flexibility is limited since altered apartments are dependent on the fixed wall positioning.

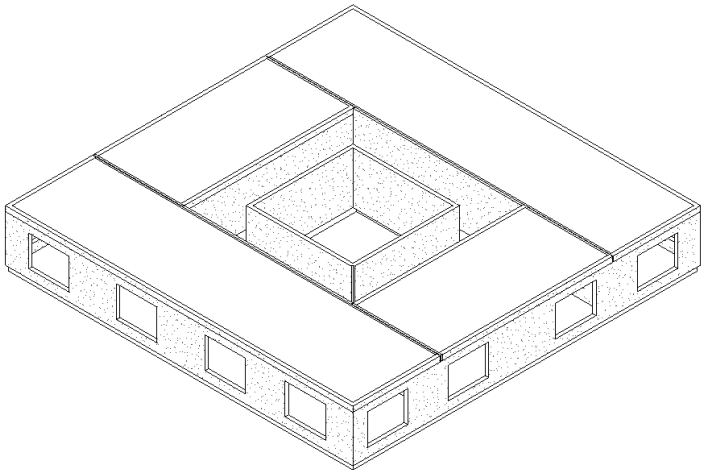

Figure 3.11: One-Way Slab Configuration 1

Configuration 2

Instead of load-bearing walls at the perimeter of the layout, this configuration uses columns at the perimeter of the building. From Configuration 2 until Configuration 4, only columns are used at the perimeter. This column placement stays fixed, since this is a more beneficial option regarding façade flexibility compared to load-bearing walls.

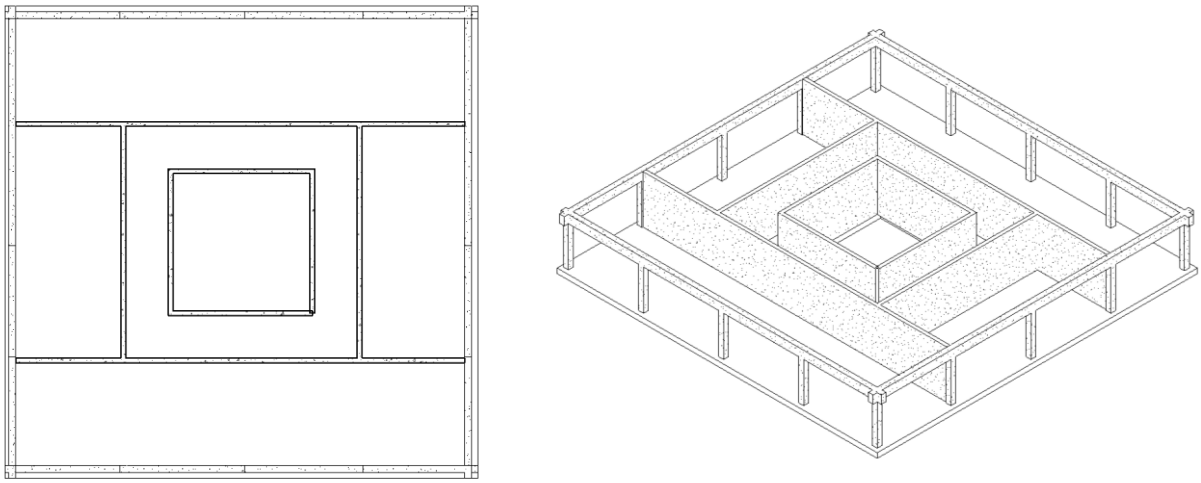

Figure 3.12: Configuration 2

The first three design configurations contain a slab system that spans in one direction, as already highlighted in the design configurations section. As a result, they need more structural support than just the core walls to help support weight. To mitigate this, Configuration 2 also incorporates load-bearing walls extending from the core which provides adequate support to stabilize the slab towards the designed direction. These are the same walls as in Configuration 1. This design still limits the goal of creating an open space without load-bearing elements in full space plan. Apart from load-bearing walls, beams are placed to connect the outer columns to the slab. As the slab only spans in one direction, these beams are crucial to transferring loads effectively to the columns, therefore minimising deflection and ensuring stability. Façade flexibility is thus upgraded, however, interior adaptability is still very limited. The interior load-bearing walls are the same as in Configuration 1, so the space plan limitations shown in Figure 3.9 also apply for this configuration.

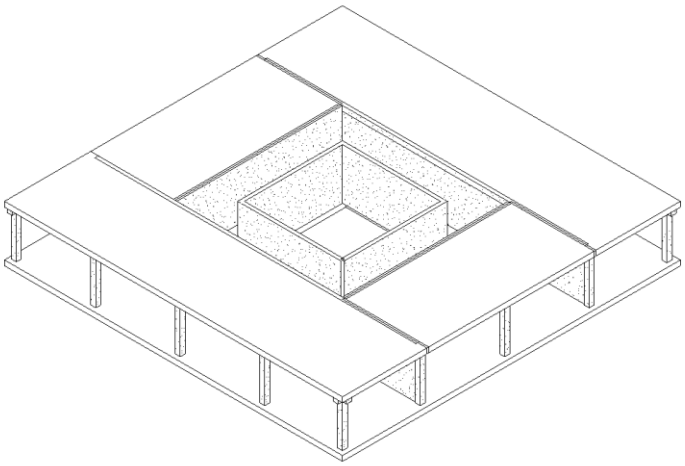

Figure 3.13: One-Way Slab Configuration 2

Configuration 3

Apart from load-bearing walls that offer support to the one-way slab, an alternative design is used for this configuration. In this design, beams support the slab. This structural shift allows for layouts that are far more flexible, since load-bearing walls no longer limit spatial development. As these fixed structural components disappear, the interior space becomes devoid of load-bearing walls and columns, enabling any type of apartment configuration and greater adaptability over the building's lifespan.

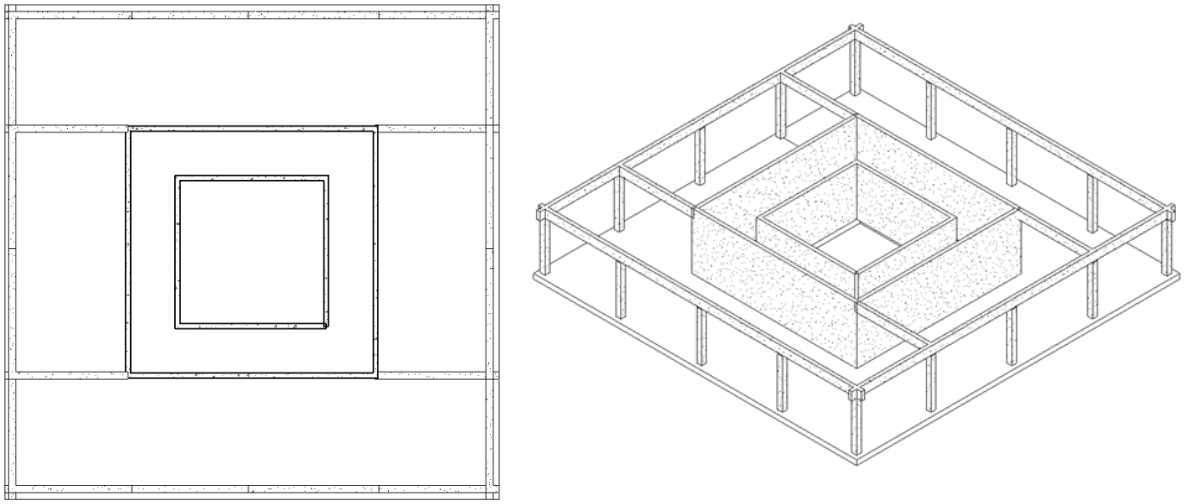

Figure 3.14: Configuration 3

This configuration is a significant enhancement in long-term adaptability and a more practical application of the open-floor plan concept. It accommodates for all four lettered space plan layouts A-D (*Appendix A*), which Configurations 1 and 2 could not allow. The only remaining restriction is the beam-supported slab, which continues to restrict interior aesthetics, but also complicates future refurbishments when altering different apartments. It is the interior adaptability of this configuration that separates it from the first two. While the façade is already fully flexible because of the column-based structure, this configuration is close enough to an optimal solution in terms of structural openness. However, it does not completely support architectural ceiling freedom, this becomes the target of the following configuration.

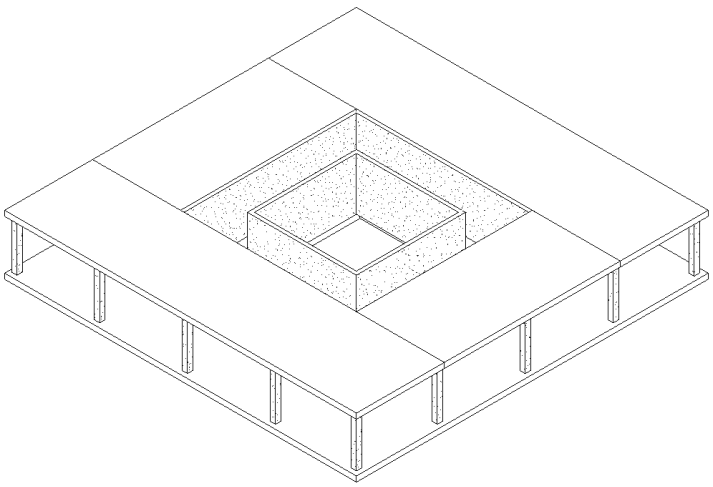

Figure 3.15: One-Way Slab Configuration 3

Configuration 4

The previous configuration almost perfectly reaches full adaptability, the only remaining limitation is architectural ceiling freedom. In order to achieve this degree of adaptability, it is necessary to redesign the structural system to eliminates beams. The way to do this is to utilize a two-way spanning slab that spans two directions to distribute the loads, as opposed to requiring supplementary support beams. This approach is used in Configuration 4, where beams are eliminated from the load-bearing structure, as the slab alone suffices to carry the load in both directions. Configuration 4, which does not possess any beams, therefore maximizes adaptability .

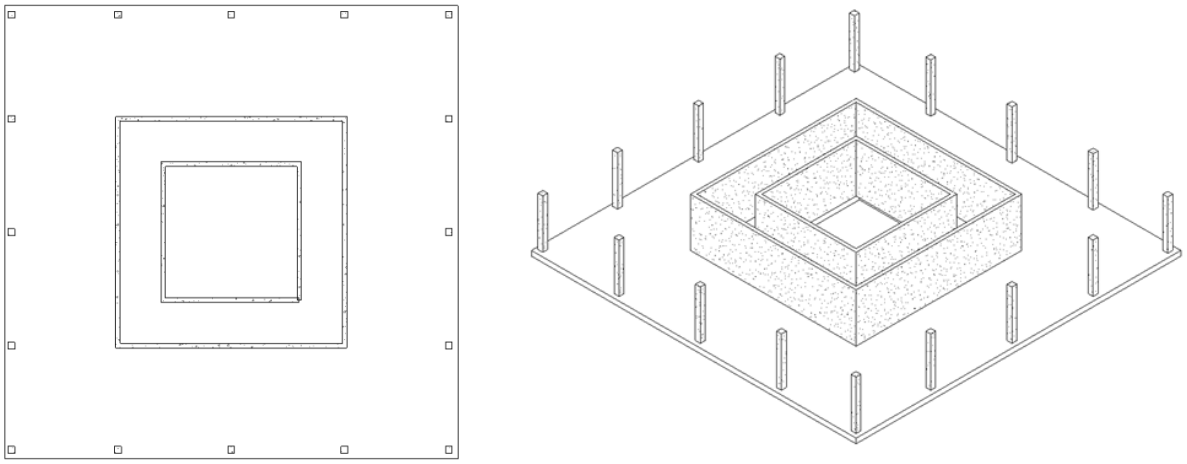

Figure 3.16: Configuration 4

Eliminating the beams provides a smooth ceiling surface, which offers many architectural and practical benefits. This makes adjusting the interior layout and renovations much easier. Since the new partition walls can be placed anywhere in the floor plan without considering the fixed beam positions, they give architects more design freedom and are less labour-intensive and time-consuming when refurbishing the space. The flat ceiling adds to the artistic quality of the interior of the building, allowing for clear, modern, and consistent spatial experiences. This is particularly true in residential buildings, where exposed beams can interfere with ceiling finishes or restrict stylistic elements in the interior, like lighting. Also, a beam-free design is favoured by MEP flexibility to allow all services to run through the ceiling zone, but this aspect is detailed in the second part of the methodology.

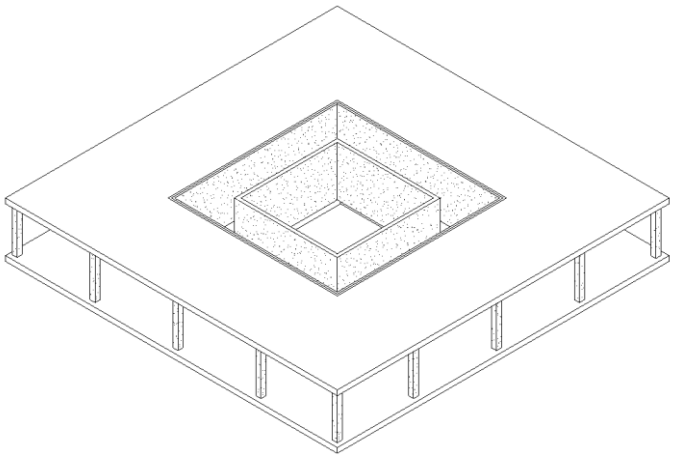

Figure 3.17: Two-Way Slab Configuration 4

3.1.4 Summary

The first part of the methodology uses a qualitative assessment to evaluate four structural configurations in terms of their capability to support long-term building adaptability. This analysis identifies three central criteria: open floor plan flexibility, façade flexibility, and architectural ceiling freedom. Each criterion is based on the degree to which a structural design can adapt to future changes. The results are summarized in Table 3.2.

	Façade flexibility	**Open floor plan**	**Open ceiling plan**
Configuration 1	Low	Low	Low
Configuration 2	High	Low	Low
Configuration 3	High	High	Medium
Configuration 4	High	High	High

Table 3.2: Structural Adaptability Assessment

Among all configurations, Configuration 4 has the highest flexibility for all criteria. A two-way spanning slab with no beams is used, allowing the user to not be hindered by structural limitations in both the floor and ceiling planes. With its smooth ceiling that contains no beams, the overall aesthetic enhances the design quality and, most importantly, provides ease of renovations and layout alterations in the future. Although the MEP advantages of such an approach are discussed in the following section, the architectural and spatial perspectives are already sufficient in establishing Configuration 4 as the most appropriate solution for long-term and future-proof dwellings.

As a result of this assessment, Configuration 4 is chosen as a structural basis to build upon in further phases of the methodology for its advanced adaptability. The design is currently only deemed quasi-optimized. Multiple MEP integration strategies within this arrangement are investigated through the subsequent Life Cycle Assessment (LCA) and Life Cycle Cost (LCC) analyses. These alternatives are intended to increase the long-term adaptability of the building, decrease environmental impact, and increase economic performance. Instead of continuing with structural systems comparisons, the next steps are devoted to MEP design options that can enable Configuration 4 to continue evolving in and help deliver a sustainable future-proof concept for a residential building.

3.2 Life Cycle Assessment

3.2.1 Introduction

Based on the principles of maximum longevity and minimum environmental impact, the second part of this section studies different MEP options for Configuration 4 according to their environmental impact, which require little demolition and less construction waste in the future. Lifecycle assessments enable the process to be optimized for sustainability.

The research involves embodied carbon calculations of different MEP options to assess the environmental impact over their total lifespan. The analysis takes periodic adaptations through the lens of Stewart Brand's layers of change. In terms of evolving residents' lifestyles, the building plan is renewed every 12.5 years, while MEP systems are replaced every 25 years, in order to keep in line with evolving devices and meet new sustainability standards. The façade is changed over a period of every 50 years to increase its functions and aesthetics, while the load-bearing structure remains the same to preserve the stability of the building.

However, it is important to note that only causes for demolition from the literature study are explored in the LCA. The renewal of the façade and accessible MEP systems aren't considered as causes for demolition. Therefore, only an alteration in the space plan layer over 12.5 years are modelled. Conclusions are made based on maintenance and repair over the different options regarding inaccessibility of MEP infrastructure.

The shift from different building layers over time speaks to the need for adaptability in any design or material selection, especially during its use and maintenance lifecycle stages. In this study, all life cycle stages are assessed, from material extraction to disposal, to ensure a full sustainability evaluation. The following simplified representation in Figure 3.18 shows the Life Cycle Assessment (LCA) process. The figure identifies the full life cycle of the building and all important stages, from the extraction of raw material to the end-of-life disposal or recycling (*Buyle et al., 2013*). The LCA process is circular in nature, so end of lifecycle materials are disposed of but can also be recycled and reused.

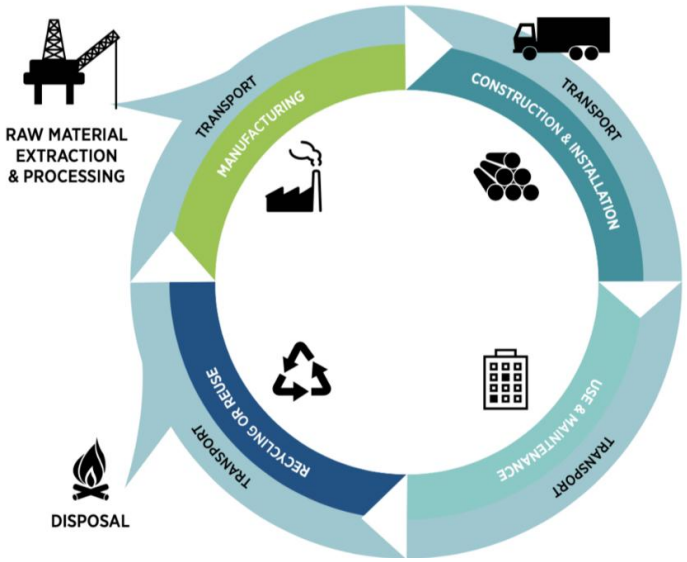

Figure 3.18: Life Cycle Stages (Morley, 2023)]

A more comprehensive overview of the LCA methodology is shown in Figure 3.19 (*Shaun, 2025)*, depicting the various lifecycle stages (A1 – A3, A4 – A5, B1 - B7, and C1-C4) that inform the total embodied carbon impact of a building. It gives an overview of life cycle-based environmental impacts for all stages of the building life cycle, from extraction of raw materials to disposal, ensuring sustainability from a complete life cycle perspective.

A1 - A3 Product stage

- **A1** Raw material extraction
- **A2** Transport to manufacturing site
- **A3** Manufacturing

A4 - A5 Construction stage

- **A4** Transport to construction site
- **A5** Installation / Assembly

B1 - B5 Use stage

- **B1** Use
- **B2** Maintenance
- **B3** Repair
- **B4** Replacement
- **B5** Refurbishment
- **B6** Operational energy use
- **B7** Operational water use

C1 - C4 End of life stage

- **C1** Deconstruction & demolition
- **C2** Transport
- **C3** Waste processing
- **C4** Disposal

Figure 3.19: LCA Life Cycle Modules (Shaun, 2025)

The product stage (A1–A3), represents the cradle-step of the product life cycle, where the materials are extracted (A1), transported to the factories for production (A2), and eventually processed into construction products (A3). This phase is very important because it includes the largest amount of embodied carbon, energy consumption, and emissions in the raw materials production.

The construction Stage (A4 – A5) includes the transport of the materials to the construction site (A4) and their installation or assembly (A5). At this stage, emissions are generated from fuel consumption during transport, energy use for construction equipment, and material wastage.

The use stage (B1–B7) includes all activities occurring during the building's operational lifetime, such as simple occupancy (B1), maintenance (B2), repairs (B3), material replacements (B4), and refurbishment (B5). The use phase often leads to demolition, since expensive maintenance, repair, and replacements can lead to the end of a building's lifespan.

Furthermore, operational energy use (B6) and operational water use (B7) can be seen in Figure 3.19. However, together with B1, these are not considered in this research. Although these factors have a significant impact on a building's carbon footprint, they do not affect decisions on how adaptable the building would be through time, and are thus outside the scope of the study. The research does not focus on operational carbon emissions.

The end-of-life stage (C1–C4) records processes associated with building demolition or deconstruction (C1), waste material transportation (C2), waste processing (C3), and disposal (C4). This phase has enormous implications for how much material is recycled and therefore influences the building's long-term environmental footprint.

Finally, Module D accounts for environmental benefits outside of the system boundary (e.g., savings from reuse and recycling of materials). However, since module D addresses secondary material uses, it is not covered within this study, which is limited to the lifecycle stages as defined (A1–C4).

This part of the methodology evaluates the life cycle of building materials to develop a comprehensive understanding of material flows, emissions, and environmental costs of various MEP options. The assessment is conducted using a cradle-to-grave approach, which is represented in Figure 3.20, meaning that the analysis covers all stages from the extraction of raw materials (cradle) to the end-of-life disposal or recycling of materials (grave).

Focusing on cradle-to-grave (*Buyle, Braet, & Audenaert, 2013*) ensures that the complete environmental impact of the materials is considered, including production, transport, construction, maintenance, replacements, and eventual deconstruction. However, operational energy (B6), water use (B7), direct building use emissions as a function of the building itself (B1), and reuse benefits or emissions outside of the building system (module D), are excluded, as they do not directly affect choices about materials and adaptability strategies. This focused scope maintains the investigation on material consumption and embodied carbon emissions across the maximum lifespan of different design options.

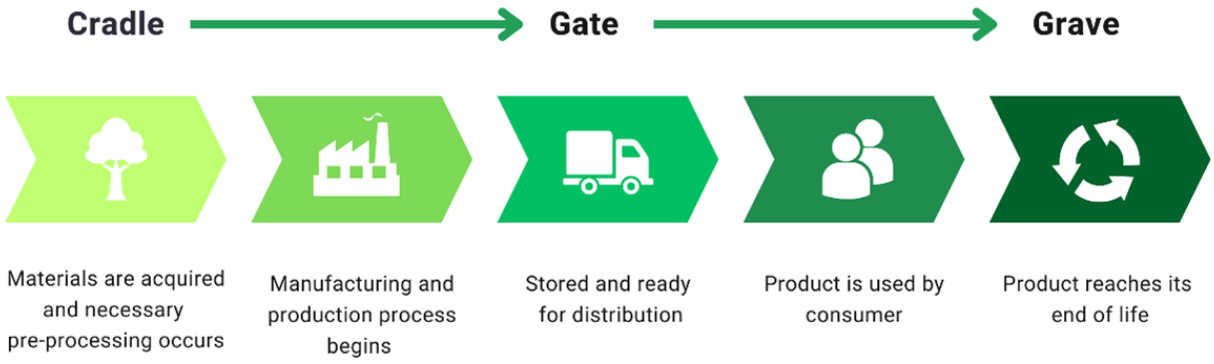

Figure 3.20: Cradle-to-Grave Approach (Green Element, n.d.)

3.2.2 Evaluation Framework and Methodology

Carbon Footprint

Now that the Life Cycle Assessment (LCA) framework is established, a quantitative approach is needed to assess and contrast the environmental impacts between various MEP approaches. One well-known measure to describe these environmental impacts is called the Social Cost of Carbon (SCC), which can be described as the present value of the monetary damage done by emitting one extra tonne of CO_2-equivalent into the atmosphere. The SCC creates a direct connection between carbon emissions and their societal and economic impacts at large, which are often calculated through a single, standardized multiplication factor.

While the SCC is capable of accounting for environmental exhaust in economic terms, for the scope of this thesis, annual carbon emissions are adopted as the most salient indicator of environmental performance. This allows for a clearer comparison of various design options with respect to one another, closely aligned to the overarching goal of reducing embodied carbon in buildings. Using carbon units instead of monetary ones to report emissions reduces confusion and also reflects with greater accuracy the long-term importance of drawing down carbon, all the more critical as governments need to meet targets. The Netherlands has committed to carbon neutrality by 2050, which requires sweeping reductions in both embodied and operational carbon. Therefore, to compare environmental impact, this quantitative measure is a useful point of comparison in this study.

OneClickLCA Methodology

OneClickLCA is used to assess the environmental impact in this study. OneClickLCA takes data from building materials, construction processes, and lifecycle stages as inputs for an LCA calculation. The workflow starts with the materials data imported from Revit. Different MEP options are designed, which differ in their design, and are imported to OneClickLCA.

The software processes this input data by assigning environmental impact factors based on the selected material types and their associated lifecycle phases (A1–C4 in this study). It calculates emissions, resource use, and environmental costs, generating a total amount of carbon emissions and an SCC score for the MEP configuration.

OneClickLCA operates according to globally accepted LCA standards, the EN 15804, which provide a standardized and reliable method for assessing environmental impacts. OneClickLCA transforms the data into monetary values linked to the Nationale Milieudatabase (NMD).

OneClickLCA Assessment Modules

As mentioned at the beginning of the methodology section, this study covers a range of LCA modules designed to evaluate the impact of different structural configurations on the environment. All of these LCA modules are affected differently by each configuration, relating to material use, adaptability, and life-cycle sustainability. Since each option is linked to specific LCA modules, subsequent sections elaborate on this relationship and the assessment method used to measure impacts. This is explained below.

1. *Construction Phase (Module A)*

The first step is to identify volumes and materials for each stage of life. At year 0, all materials to construct the building are measured. The material quantities differ over different options and therefore result in different environmental impacts for module A.

In OneClickLCA, multiple life-cycle stages are evaluated through a combination of environmental product declarations (EPDs) as well as preconfigured datasets and user inputs. Data for the A1–A3 phases (raw material extraction, transportation to manufacturing, and production) is sourced directly from EPDs, allowing material-specific environmental data to be taken straight from the Nationale Milieudatabase (NMD) or other databases. A4 and A5 phases, considering transportation to the construction site and installation processes, are calculated according to project-specific parameters. A4 then needs the transport distances and types of vehicles, while A5 requires percentages of construction waste and energy consumed in the installation process.

2. *Use Phase (Module B)*

The use phase follows the Stewart Brand principle, where each 12.5 years the space plan is changed. All the options are assessed during the use phase based on maintenance, repair, and refurbishment.

With the exception of direct operational use (B1, B6, B7), which is excluded in this study, use phase (B1–B5) parameterization depends entirely on user defined material replacement cycles: B2 (maintenance), B3 (repair) and B4 (repair). These cannot be modelled directly in OneClickLCA, so they are excluded from numerical calculations. Instead, their influence is assessed qualitatively, based on logic and not software driven data.

This study introduces a space plan that evolves over time. This process is mainly explored in development to Module B5 (refurbishment). However, since it is not possible to directly model these layout changes in OneClickLCA, it is evaluated manually. The new material required and construction waste generated during each refurbishment cycle is calculated independently. The procedure for these calculations is discussed further in this paper.

3. End of Life (Module C)

Demolishing the structure, means more construction waste. These materials impact module C2 (transport) and Module C3 (waste handling). New material production (Module A) has an enormous amount of carbon emissions, demolishing a structure on the other hand, has lower carbon emissions. Modules C2 and C3 are automatically calculated within the OneClickLCA software.

The end-of-life phase (C1–C4) is an essential element of the Life Cycle Assessment (LCA), but it is not fully considered in this study. Specifically, the techniques of dismantling or demolishing a building at the end of its life cycle (Module C1) and the final disposal of materials through landfilling or incineration (Module C4) are not factored into this study. Module C1 involves the energy and equipment required for demolition, the labour force engaged in taking apart the structure, and the emissions produced through this process. However, as this study aims to avoid demolition altogether by prioritizing adaptability and structural longevity, delving too deeply into Module C1 would stray from the intended goals and scope of the research. Similarly, Module C4's focus on recycling strategies holds little relevance, as optimizing the structural design for extended usage remains the emphasis rather than recycling plans.

More important than the emissions coming from Module C is when the end-of-life stage occurs. Demolition and waste processing (Modules C2 and C3) have a relatively low impact compared with new material production. But, rebuilding comes after demolition. When a structure is demolished long before its theoretical lifespan, the embodied carbon of the new structure (reflected in a new cycle of Module A emissions) is therefore realized much sooner than necessary. Table 3.3 gives an overview of the modules and their relevance to the study and the OneClickLCA software.

Module	**OneClickLCA Usage**
A1-A5	Comprehensive assessment with Environmental Product Declarations and detailed data from Nationale Milieudatabase Phases A1–A3 are based directly on published EPDs, while A4 and A5 were estimated based on project-specific parameters such as means of transportation and expected waste produced during construction. A1 to A5 are not shown separately in the results, but are combined as a total.
B1, B6, B7	Excluded from this study. These operational use phases are not assessed using OneClickLCA.
B2, B3, B4	Excluded from quantitative calculation since certain impacts cannot be precisely determined using this program. Their effects are instead considered through interpretations rather than model-driven results.
B5	Not directly displayed in OneClickLCA. Instead, refurbishment are evaluated manually, with calculations, with the help of OneClickLCA for new material requirements and construction waste.
C1, C4	Not taken into account. Consequently, demolition (C1) and final decommissioning (C4) were deemed irrelevant for the objective.
C2, C3	Taken into account: waste handling, transport, and processing helps capture end-of-use impacts for a more holistic perspective.

Table 3.3: Overview of OneClickLCA Usage per Lifecycle Module

3.2.3 Options

In this part of the study, flexibility and longevity of the structure are assessed by the placement of mechanical, electrical, and plumbing (MEP) systems. When MEP systems are embedded into the slab, any future changes require large structural modifications, which is highly impractical, leaving little recourse for adaptability. For this part of the study, four different options of MEP configurations are explored with LCA and LCC, therefore optimizing the load-bearing structure further for longevity. Since market demands cannot be predicted, also qualitative analysis has been used for assessing effects of renovation and maintenance. From Configuration 4, now five options of MEP design are configured:

Option 1 : MEP is embedded into the slab. In traditional MEP design, future space plan changes are not taken into consideration. If changes in apartment sizes are required, slabs have to be demolished. While this is highly impractical and unrealistic, a theoretical approach is used to illustrate and quantify the limitations of the current design.

Option 2: Additional MEP infrastructure integrated into the slab, which creates further channels, or routes for systems like ventilation to plumbing. The advantage of pre-integrating these additional service routes contributes to more flexibility in shifting apartment layouts, can be relocated more easily without the need for major MEP re-routing or demolishing concrete slabs. It makes the space plan more dynamic, despite the fact that the infrastructure remains embedded at a structural level.

Option 3: This solution effectively embeds MEP services outside the load-bearing slab, placing the services in a layer of foam concrete above the structural slab, This allows for easier access and future modifications, as foam concrete is non-structural and easier to remove (unlike systems embedded in concrete slabs).

Option 4: This solution has dedicated void space routing MEP services above the structural slab, which provides full access without structural demolition. The separation between services and structure enables easy reconfiguration of space plan layouts, but also simplifies maintenance and repair.

Option 5: This arrangement puts MEP services fully below the structural slab, within the ceiling. No demolition or disruption of the building or finishes is necessary to maintain, replace, or reroute services.

Across all options, the floor-to-ceiling height remains the same, with a height of 2.6 meters. However, floor-to-floor height is not fixed, since different strategies require different floor heights.

Option 1

Option 1 shows the traditional floor design in which the MEP is completely cast into the structural slab. As the diagram indicates, the round and square symbols mark service routes, that is, plumbing pipes and ventilation shafts, that were cast directly into the slab during construction. The floor-to-ceiling height measures 2.60 meters (constant over all options), with a total floor-to-floor height of 2.90 meters. In this instance, a 250 mm thick structural slab with a 50 mm of finishes which consists of insulation and other adhesive layers.

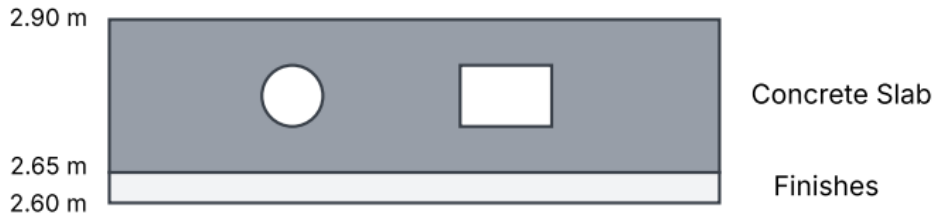

Figure 3.21: Option 1: Embedded MEP Design

Module A:

The calculation for Module A is performed with OneClickLCA starting from material volumes (obtained from the Revit model). A total of 51940 kg CO_2-eq of embodied carbon emissions were produced for this stage (*Appendix B)*.

Module B:

Maintenance (B2): MEP services are considered inaccessible in this option. Since the pipes are embedded directly into the structural slab, no preventive maintenance can take place without destruction. It is highly impractical and financially unbeneficial to demolish the slab for purely inspection or maintenance purposes. Therefore, this process is not carried out.

Repair or Replacement (B3/B4): This Module is affected when a pipe or service fails. Partial demolition of the slab is now needed over a larger area to fix the failed infrastructure. The environmental impact of breaking and pouring new slab is 84.21 kg CO_2-eq/m² according to OneClickLCA. For example, if in a 50 m² apartment half the floor (25 m²) would need to be demolished to find and repair a leak, this results in an additional carbon emission of about 2,105 kg CO_2-eq.

Module B5: Retrofitting the apartments cannot be done. Altering different apartment configurations is very unlikely, since the process of demolishing the slab is too expensive and too disruptive. Therefore switching apartments won't be configured. The initial design with the amount of kitchens, bathrooms, toilet etc. does not change over time. The only option is to make configurable rooms which share kitchen and/or toilet, to act on these market opportunities.

Module B calls out the inherent limitations with embedding MEP services within the structural slab, as is common in the traditional approach for many residential buildings. Maintenance activities (B2) become almost impossible and involve breaking the slab even for minor repairs. Under B3/B4, however, this translates to economically and environmentally expensive interventions in the event of service failure. Moreover, retrofitting the apartment layout (B5) is almost impossible, since almost the whole floor would need to be demolished. All of these limitations lead to a rigid building configuration incapable of evolving with shifting user requirements and market forces.

Module C:

Carbon emissions from Module C are equal to 1192 kg CO2-eq. The impact of demolishing the structure is almost negligible, compared to Module A. But what's more essential is when the building gets demolished. The goal is to create a highly adaptable building which can act on market opportunities, but as this option does not work, it must at a sudden point get destroyed. Pipes have a lifespan of around a maximum 100 years, which means that this would also be the maximum lifespan of the building as replacing these is too expensive compared to demolishing the structure. The reason for earlier demolition would be housing vacancy. This is something which cannot be predicted, and therefore the building could get destroyed at any point, meaning the annual emissions can differ a lot. These emissions can be calculated with:

$$\textit{Annual emissions} = \frac{Module\ A + Module\ B + Module\ C}{Building\ Lifespan}$$

For now Module B is not taken into consideration. The lower the lifespan the higher the annual emissions. Table 3.4 shows how the annual emissions differ when increasing the lifespan of the building. For example going from 30 to 50 years reduces annual emissions by 40%.

Demolished at Year	Annual Emission
10	5313,2
20	2656,6
30	1771,07
40	1328,3
50	1062,64
60	885,53
70	759,03
80	664,15
90	590,36
100	531,32

Table 3.4: Annual Emissions Option 1

Option 2

In Option 2, as illustrated in the drawing, additional paths for mechanical, electrical and plumbing (MEP) services are cast into the structural concrete slab. These extra services are embedded to allow for different permutations of apartments over time. The overall floor-to-floor height remains the same at 2.90 meters, due to a single 250 mm thick reinforced concrete slab and 50 mm for finishes. The only difference is more MEP channels than necessary are included in the initial design.

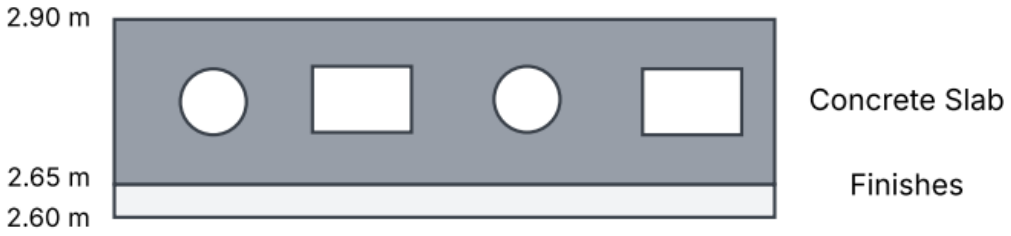

Figure 3.22: Option 2: Pre-Integrated MEP Channels

Module A:

Option 2 has the exact same dimensions as Option 1, where the load bearing structure is preserved with the same volume and configuration of material (*Appendix B)*. Nonetheless, more MEP infrastructure is integrated into the slab to allow space plans to be modified in the future. Although module A also has the same structural materialisation as in Option 1, it does not include all the additional infrastructure embedded in the concept and the design from the beginning. This leads to more upfront material use and thus higher embodied carbon. However, embedded MEP routes could go unused due to unpredictable housing markets. Since these are unknown at the time of designing the building, there might be MEP infrastructure designed that ends up unused as construction waste. To gauge the effect of this extra infrastructure, average embodied carbon figures are applied:

- Extra brass piping: 22 kg CO_2-eq/m
- Extra plastic piping: 20 kg CO_2-eq/m
- Extra ventilation duct: 13 kg CO_2-eq/m

These numbers represent the possible carbon impact of future flexibility, providing extra MEP infrastructure when the building is originally designed. Even though the optimization of the MEP design is not included in the scope of this thesis, a simplified example can still explain the main idea well. For example, floor layout C can be built ahead of time in anticipation of future conversion to layout D, requiring the installation of MEP infrastructure in advance for an additional six apartments. The assumption is made that an extra length of 8 meters of ventilation and plumbing is needed per apartment, multiplying this by 6 apartments results in an additional infrastructure of 48 meters.

When considering the emissions from above, the total emissions are 20 kg CO_2-eq/m (plastic) for plumbing and 13 kg CO_2-eq/m for ventilation, which brings the total to 33 kg CO_2-eq/m. This means that the added infrastructure per floor adds approximately 1,584 kg CO_2-eq. Converting this to a 15-story building, results in an increase of 23,760 kg CO_2-eq in embodied carbon.

In case this embedded infrastructure is eventually put to use, such a move can be seen as a way to invest in future-proofing. However, market dynamics are unpredictable, and if the demand for student housing (layout D) does not materialise then a lot of this pre-installed infrastructure could go unused, leading to unnecessary construction waste. From an economic perspective this would also be unfavourable if this extra infrastructure would ends up unused.

Module B:

The conclusions for maintenance (B2) and repair/replacement (B3/B4) are unchanged from option 1. MEP services, being embedded within the slab, make maintenance impossible, and repair and replacement very difficult.

However, for this option, retrofitting (Module B5) scores higher. Added MEP infrastructure is incorporated into the slab, allowing for reconfigurability of future apartment layouts. This foresight enhances spatial adaptability, enabling the building to adapt to changing market demands without major structural changes. While this strategy does result in increased embodied carbon upfront (as discussed in Module A above), it also allows for more flexible and cost-saving retrofitting scenarios over the lifetime of the building.

Module C:

The end-of-life emissions (Module C) are unchanged in this option relative to Option 1, neither the material composition of the structural system nor the demolition process are affected. However, despite the better adaptability in terms of layout reconfiguration (B5), the building cannot realistically have a lifespan that reaches 100 years old. While constraints on space planning are partially addressed in this option, accessibility to embedded MEP services is simply not possible. Long-term serviceability is therefore a limiting factor on the design life, since if services become unreliable beyond repair, the slab itself must be demolished. Thus, whilst emissions per demolition remain the same, the rate of demolition over time is still too high for this to be considered a genuinely future-proof setup.

Option 3

Option 3 clarifies the separation of load-bearing slab from MEP systems, by means of a non-structural foam concrete layer positioned on top of the structural slab as shown in Figure 3.23. This arrangement allows the main slab to span 200 mm thick and a 250 mm thick foam concrete layer is placed on it to accommodate the MEP installations. This results in a floor-to-floor height of 3.10 meters. The foam concrete layer is easier to cut than structural concrete.

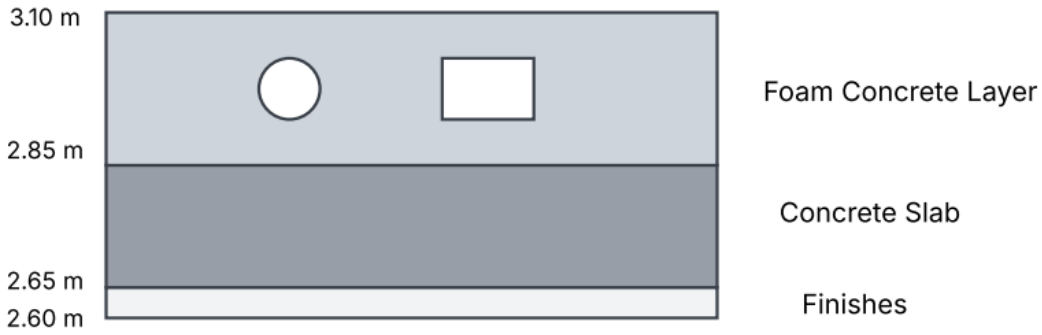

Figure 3.23: Option 3: MEP Embedded in Foam Concrete Layer

Module A

The embodied carbon emissions of Option 3 are equal to 61,199 kg CO_2-eq (*Appendix C)*, which is substantially greater when comparing to Options 1 and 2. This is primarily due to the introduction of the 250 mm thick foam concrete layer placed on top of the structural slab for embedding MEP infrastructure. Even though the foam concrete is lightweight and non-structural, it does add a significant amount of cement-based material emissions through the production phase. Option 3 essentially adds a complete additional material layer to the full surface of the floor slab, resulting in higher material volume, and therefore increasing embodied carbon emissions.

Module B:

Maintenance (B2): In this configuration, MEP services are accommodated within a non-structural foam concrete layer above the structural slab, which makes it technically viable to give MEP services accessibility for maintenance. In reality, though, preventive maintenance is limited because gaining access to these systems requires localized floor-surface demolition, which can disrupt residents and generate construction waste.

Repair or Replacement (B3/B4): foam concrete shows improved serviceability over slab-integrated systems. Foam concrete can be cut with relative ease to achieve localized access to MEP for repair or replacement. This eliminates any structural damage. However, every repair produces embodied carbon and construction waste. The environmental impact of repair or replacement actions is estimated at 24.48 kg CO_2-eq m^2 which is a drastic reduction when compared to Options 1 and 2, however it is still not a highly practical option.

Module B5: The load-bearing slab is left untouched, making retrofitting and spatial reconfiguration technically possible in this design. Apartment plans can be changed without structural demolition, a clear advancement in the area of adaptability. Although it is more flexible than conventional embedded systems, the destruction of materials makes the model never entirely circular or waste-free.

Module C:

The expected impact on carbon emissions related to module C is 1,155 kg CO_2-eq for option 3. However, compared to traditional embedded systems like option 1 and 2, which are demolished and rebuilt once the service life is depleted, phased retrofitting and replacement in this configuration supports a longer lifespan. Thus, the entire building lifecycle is estimated to be 200 years, which drastically decreases the amount of complete cycles of reconstruction. The operational phase can be extended, as the lightweight foam concrete layer may be partially removed locally for intervention during the life cycle of the building, with the structural system remaining intact and avoiding emissions during the disposal stage.

Option 4

In contrast to Option 3, where MEP services are embedded within a solid foam concrete layer, Option 4 takes a less invasive and more effective approach by forming a dedicated service void above the structural slab. MEP infrastructure can now be routed inside this void, making them accessible without the need for demolition.

Figure 3.24: Computer Floor (HT Raised Floor, n.d.)

In office buildings, service voids are frequently created with raised access floors (also called computer floors, see Figure 3.24). Such systems are in the form of modular panels that are raised above the structural slab to allow a continuous space for routing mechanical and electrical services. These types are especially suited for routing power cables, data lines and other low-impact infrastructure, allowing quick access for maintenance, upgrades and spatial reconfiguration. Although common in commercial buildings, their use is rare in residential buildings because the spatial and technical requirements differ greatly. Residential buildings have more integrated sanitary and plumbing systems, which raises the question whether raised floor systems can be effectively applied. But if this kind of solution were applied effectively in some way, it would allow for reconfiguration of apartments over the years.

This approach creates a complete service void above the structural slab where plumbing and ventilation (MEP) services can easily be routed without interfering with the structural system. The empty space is topped with a modular concrete panel serving as a removable walking surface, which can be lifted to expose or reconfigure services as required. Here, the total height from one floor to another in this design is 3.20 m (consisting of a 200 mm structural concrete slab, a 300 mm clear void and a 50 mm ceiling finish). The next page presents two conceptual applications of raised floor systems to provide vivid examples of the way this principle can be applied to residential buildings.

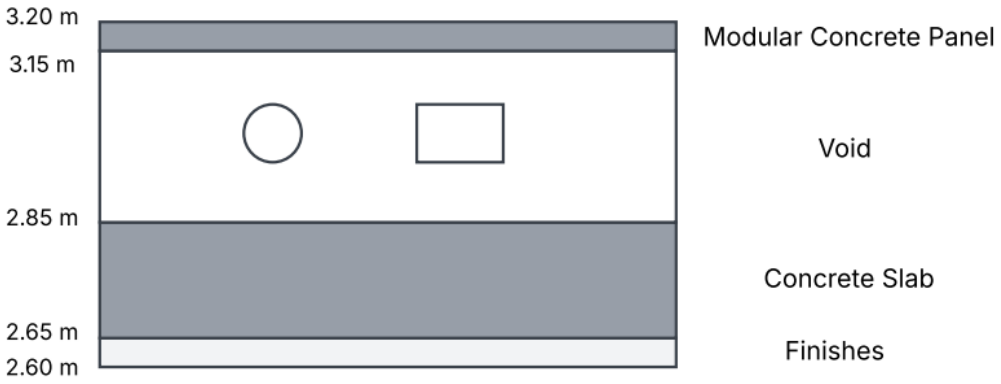

Figure 3.25: Option 4: MEP in Raised Floor System

Example 1: Geoplast Modulo

The permanent formwork system, Geoplast Modulo, (Figure 3.26) creates an accessible void under a concrete walking surface. Made of lightweight plastic, arranged in a modular grid, which are often overlaid with a layer of concrete. It creates a ventilated underfloor space to route mechanical, electrical and plumbing (MEP) services without the need for embedding them into the structural slab.

Figure 3.26: Matix Module (Geoplast, n.d.)

The system was originally developed for ventilated foundations and crawl spaces but can be the solution for adaptable floor designs, particularly where future adaptability or maintenance access is contemplated. However, although not yet used in residential buildings, it has been used for foundations and parking spaces, which demonstrates the high-load bearing capacity. In practice, these modules almost always get filled with concrete, which should be avoided in the design of this structure to maintain flexibility.

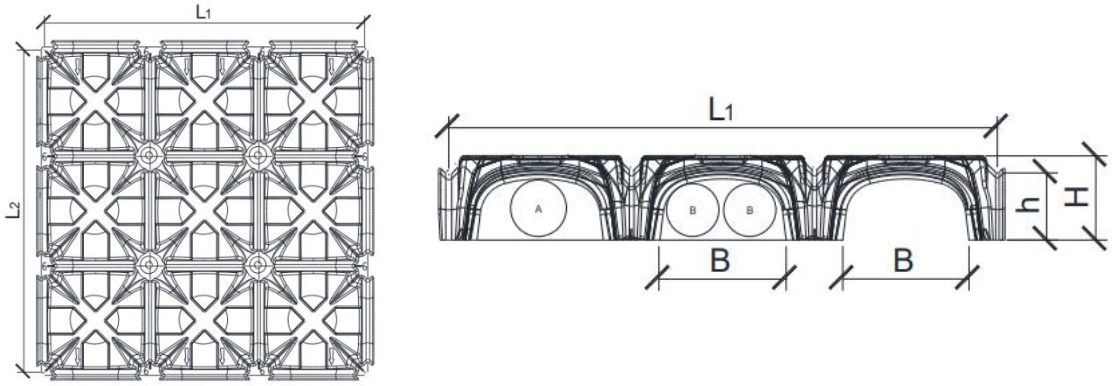

Figure 3.27: Technical Drawings of Raised Floor System (Geoplast, n.d.)

Example 2: Pedestals

This example shows a pedestal-based raised floor system, which is typically applied in offices, but also in gardens. In this system, modular floor panels are supported on adjustable pedestals, creating a service void underneath the walking surface. This gap facilitates the distribution of MEP services like pipes, cables, and ducts. The system is dry and demountable, making it ideal for spaces that require frequent access to infrastructure. Because of the open structure and modularity, this example uses less plastic material than closed-form systems like Modulo.

Figure 3.28: Pedestal Raised Floor System (Xypedestal, n.d.)

Module A

In total, the embodied carbon emissions for Option 4 are equal to 59,282 kg CO_2-eq (*Appendix D)*. This value includes the materialisation of the structural slab and also makes use of plastic matrix modules of Example 1, which open up a service void above the slab to elevate services above the slab. Since there was data available about the materialisation (*Geoplast, n.d.)*, this design has been chosen for the calculation. Although the structural slab itself has a volume similar to the other options, the added plastic (around 1,883 kg of polypropylene) translates into a larger carbon footprint in the production phase (Module A). To top it all off, the matrix system has 50 mm of prefab concrete topping which adds additional emissions.

Module B

Maintenance (B2) : This option allows MEP services to be run wholly in a dedicated and open void created by the plastic matrix system. By just removing the floor panels and topping layer, full access to services from above is made possible. Hence, preventive maintenance is indeed possible without damaging the structure, making it a highly serviceable option.

Repair or Replacement (B3/B4): MEP elements can be repaired or replaced without too much disturbance. As no demolition is needed, interventions are targeted and efficient, with extremely low embodied carbon. Lifting floor finishes or opening inspection zones could have only a slight effect.

Module B5: Option 4 allows substantial spatial reconfiguration for the future. Keeping the load-bearing slab and the MEP infrastructure unaltered during layout changes means that apartments can be redivided, expanded, or merged without structural demolitions. The borrowed void space can be used for new service routes, enabling kitchens, bathrooms, and technical spaces to shift in response to changing market demands.

Module C

Option 4 has end-of-life carbon emissions of 5,105 kg CO_2-eq. Even though these plastic matrix elements have a lower embodied carbon impact for Module A compared to concrete, Module C had a larger influence due to waste processing. In contrast to concrete elements that can be broken down and reused as aggregate, plastic components are still not a common input in the construction sector for recycling and in most cases are considered waste. However, due to high maintainability and significant flexibility of the services, Option 4 for can easily reach a 200-year lifespan without a high amount of construction waste during the use phase.

Option 5

For Option 5, all MEP (mechanical, electrical, and plumbing) services are located below the structural slab within a ceiling service zone. MEP infrastructure runs independently from the structural slab and allows maximum flexibility and ease of access without the need to alter or penetrate the concrete slab. For this solution, the entire floor-to-floor height becomes 3.10 m on the basis of a 50 mm finished ceiling and 200 mm deep service void.

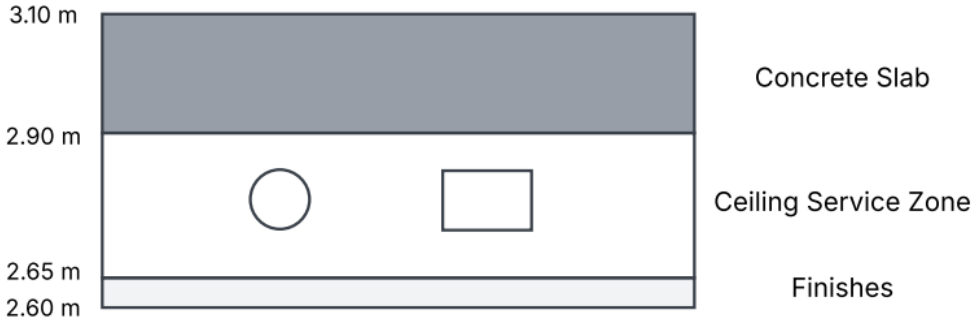

Figure 3.29: Option 5: MEP in Suspended Ceiling System

Module A

The Module A embodied carbon emissions for option 5 is 48,487 kg CO_2-eq (*Appendix E)*, the lowest emission among the four configurations. It situates all MEP services under the structural slab in an enclosed ceiling area. This allows the slab thickness to be reduced by 50 mm compared to Option 1. A significant reductiom of concrete volume reduces the carbon footprint in the material production stage.

Module B

Maintenance (B2) : the MEP services are fully exposed and/or can be accessed easily in ceiling zone under the structural slab. This setup also allows for regular inspection without demolition or invasive interventions. Consequently, preventive maintenance becomes both feasible and practical, with increased service life for residential buildings.

Repair or Replacement (B3/B4): In the event of a failure, the ceiling can be opened which allows for fast and effective localization and interventions. For repair and replacement, no significant amounts of material waste result since only surface-access panels or lightweight coverings need to be removed, which can be made modular. This considerably lowers the carbon impact in the case when repair or replacement is needed.

Module B5: This option provides complete flexibility on layout changes for the future. Because the services are not integrated into the structure and are wholly independent of the load-bearing system, apartment layouts can be changed without structural demolition. New service connections can run in the ceiling zone to accommodate changed layouts, allowing long-term flexibility with negligible construction waste.

Module C

Carbon emissions associated with module C are the lowest among all options at 1,101 kg CO_2-eq. This slightly reduced impact is because of the smaller structural slab used. Crucially, the high level of adaptability and service accessibility makes this configuration suitable for building lifespans of up to 200 years, or even longer.

3.2.4 Scenario Modelling LCA

The following is a scenario based modelling to show the environmental impact of the five options. From the Stewart Brand model every 12.5 years the space plan changes. For the changing of the space plan from one to another, the assumption is made that 25% of the slab needs to be destroyed. This is important for Option 1 and for Option 3.

For Option 1 however, this is an unrealistic scenario, breaking through the slab with reinforced concrete is not realistic and too expensive, therefore this will never be done in reality. This option has been elaborated to show what the impact would be if adaptability is needed in a traditional design. However, Option 3 could be possible since foam concrete is not that heavy and does not contain any reinforcement. The effect of Module B is calculated with:

$$\mathbf{B5_{total\ emissions} = \sum A1\text{-}A5_{new\ materials} + = \sum C2\text{-}C3_{old\ materials}}$$

Where: $-\sum A1\text{-}A5_{new\ materials} = A1\text{-}A5_{new\ walls} + A1\text{-}A5_{new\ slab}$

$$-\sum C2\text{-}C3_{old\ materials} = C2\text{-}C3_{old\ walls} + C2\text{-}C3_{old\ slab}$$

To address the uncertainty of predicting the actual lifetime of buildings, this research uses lifespan assumption model. This modelling includes three scenarios: worst case, mid case, and best case, with the difference across the scenarios driven by different assumptions concerning the lifespan of the buildings. These assumptions, explained in the literature study, are based on the lifespan of MEP infrastructure, which lasts about 75-100 years. Options 4 and 5 which are built with accessible services are not influenced by early failure and are therefore assumed to reach lifespans of over centuries. Option 3's lifespan is assumed to range between Option 2 and Option 4 and 5.

- **Worst case**: MEP failures can lead to early demolition: frequent failures that force early demolition since repair is too expensive and impractical. The average lifespan of MEP is therefore not reached for embedded systems and is estimated at 50 years.
- **Mid case**: this case assumes an average performance for the MEP infrastructure, where failure does not occur, which is around 75 years for embedded systems.
- **Best case:** assumes MEP systems can last for 100 years without significant failures, allowing buildings to fulfil their longevity potential.

As mentioned earlier, plumbing and ventilation materials are not part of the analysis, since their replacement cycles are the same for all configurations and their exact volumes lie outside the scope of this study. 25% of the slab is assumed to be demolished during reconfiguration, this is a theoretical simplification for comparison only. A change in this assumption is not needed since changes in this percentage would have no impact on the study's findings overall. The results can be seen on the next page and the calculations can be found in *Appendices F-H*.

3.2.5 Environmental Impact

Frequent failures of MEP systems in the worst-case scenario lead to premature deconstruction. The two options that rely on slab-embedded MEP systems (Options 1 and 2) are very vulnerable to this outcome. Option 1 fares particularly badly, for its rigid structure cannot realistically be reconfigured, and its high carbon emissions for its short 50-year life contribute to a poor overall score. Option 2 is slightly better because the service routes were finalized beforehand, but it is overall still likely to be considered obsolete relatively early. Option 3 is more accesible; however, it still produces construction waste due to cutting of the slab. In contrast, Options 4 and 5 are able to operate at low annual emissions even under the most pessimistic assumptions, resulting in a 200+ year lifespan.

Worst case	*Carbon emissions (kg CO_2)*	*Lifespan (years)*	*Annual emissions (kg CO_2/year)*
Option 1	72079	50	1442
Option 2	53132	50	1063
Option 3	71534	75	954
Option 4	74777	200	374
Option 5	49588	200	248

Table 3.5: Annual Emissions – Worst Case

In the mid-case, where MEP systems function adequately and do not trigger an early demolition, the performance gap narrows slightly, but the structural efficiency limitations of Options 1 and 2 remain the worst options. On average, pipes last about 70 years, so the lifespan of embedded structures is set to 75 years. The extra MEP infrastructure could expand the lifespan to 100 years. Options 4 and 5 remain ahead despite the same life expectancy assumptions, demonstrating that their performance is stable.

Mid Case	*Carbon emissions (kg CO_2)*	*Lifespan (years)*	*Annual emissions (kg CO_2/year)*
Option 1	84711	75	1129
Option 2	53132	75	708
Option 3	75206	100	752
Option 4	85167	250	341
Option 5	49588	250	198

Table 3. 6: Annual Emissions – Mid Case

The contrast between the design variants is even more pronounced when MEP systems perform better than expected and buildings deliver their full design potential. Since the maximum lifespan cannot be known beforehand, it could be the case that the structure with Option 4 or 5 survives for 300 years. In contrast, Options 1 and 2 do not have a greatly increased lifespan, where their original structural and service design disadvantages continue to produce higher yearly emissions. After 100 years of operation, the whole MEP infrastructure needs to be removed and repaired, giving demolition preference. Option 3, on the other hand could be maintained however does require a lot of labour. But in the best possible scenario it is considered economically viable.

Best Case	*Carbon emissions (kg CO_2)*	*Lifespan (years)*	*Annual emissions (kg CO_2/year)*
Option 1	97342	100	973
Option 2	53132	100	531
Option 3	89894	200	449
Option 4	85167	300	284
Option 5	49588	300	165

Table 3.7: Annual Emissions – Best Case

Figure 3.30 displays all options over all scenarios in one figure. Note that Option 1 is ruled out for making conclusions, since it represents a non-viable configuration that would never be applied in practice. For the rest of the configurations, placing MEP systems in a location other than the concrete slab significantly reduces emissions over the lifetime of the building. For quantitative conclusions, Option 2 and 3 have been compared with Option 4 and 5. This investigates solutions which use out-of slab methods vs inside slab solutions, and shows that the out of slab approach decreases embodied carbon by:

- 69% in the worst-case scenario
- 60% in the mid-case
- 54% in the best-case

That translates to an average impact reduction of 61%, evidencing that running MEP separately from the structure effectively reduces environmental impact, regardless of performance level. Options 4 and 5 are the most stable and resilient across all scenarios. Their annual carbon emissions change very little between the worst, mid and best case, suggesting that these configurations are in general less sensitive to system failure.

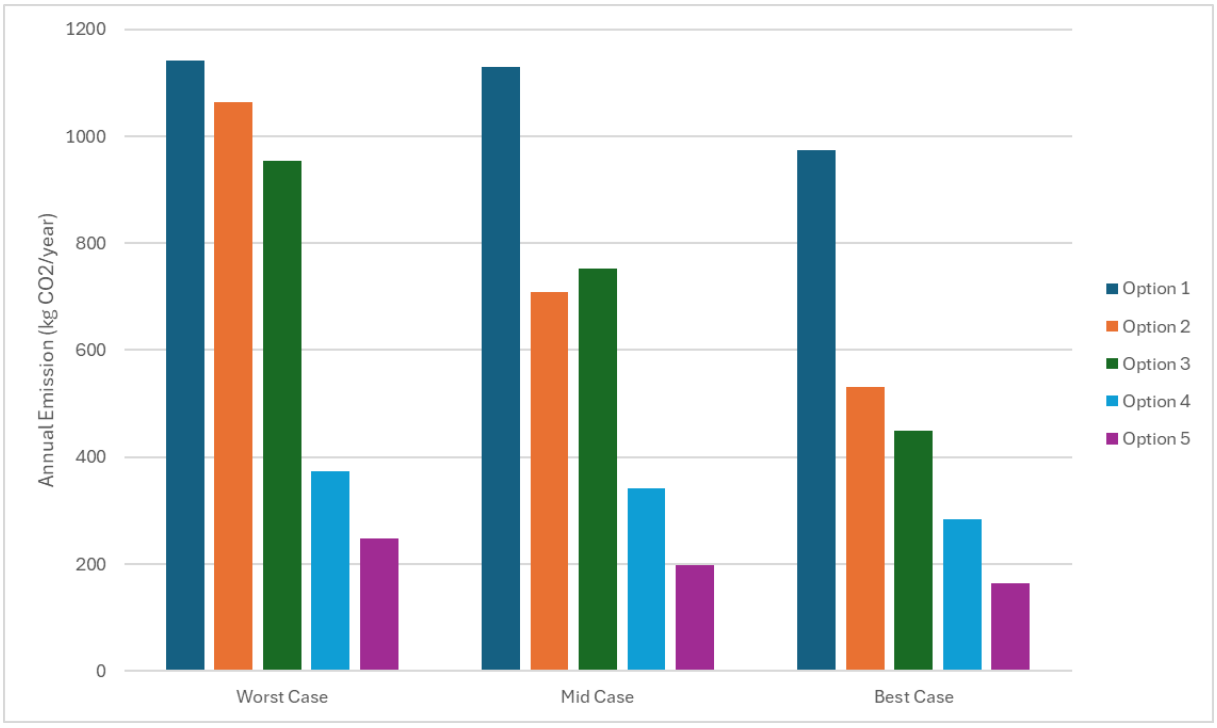

Figure 3.30: Comparison of Annual Carbon Emissions

In an optimistic scenario, Option 3 with a non-structural foam concrete layer, also reaches a relatively good score. While more material is consumed in the process, the design allows for possible replacement of the MEP services. Option 2 allows a good option when lifespan is not considered, this option does not require demolition during the refurbishment processes, however, since MEP is still embedded inside the slab, its lifespan is still limited. On the other hand, Option 1, with MEP infrastructure integrated directly into the load-bearing slab, proved to perform poorly regardless of scenario. It creates an enormous amount of material waste and need for demolition even under the best conditions, and has limited capacity to facilitate sustainable long-term operation of the building.

3.3 Life Cycle Cost Analysis

The economic aspect of a building can be understood not only in relation to the cost of construction, but rather the long-term financial viability of a building, involving ongoing renovation and demolition expenses. The following analysis outlines the Life Cycle Cost (LCC) of the different MEP options and shows how their design and lifespan play a role in economic outcomes.

Each configuration is unique in longevity and frequency of demolition. Some designs provide for long-term adaptability, while others have a shorter functional lifespan that leads to earlier replacement and higher long-term costs. Cost escalation due to inflation is more pronounced for configurations with a shorter lifespan, as demolition involves investing in the same material and labour at inflated future prices when constructing a new building. The analysis presented aggregates how refurbishment strategies and adaptability, as informed by LCC principles, can mutually affect the total cost of ownership throughout the building's life cycle.

Optimising buildings for adaptability, therefore, not only underpins sustainability aspirations, but also delivers longer-term financial benefits. In this part of the methodology, an LCC is carried out, but before jumping into calculations, some benefits are explained of planning for flexibility from the start.

3.3.1. Benefits

1. Tender Advantages

Future-proofing reduces the Environmental Cost Indicator (ECI) value of a building. This number reflects the overall environmental footprint of a project in terms of energy, CO_2, and the amount of waste produced during its complete life cycle. A lower ECI score means a much more sustainable and circular design, which corresponds to the existing national and EU sustainability targets. These objectives are increasingly being informed by the goals of Paris-proof design, which seeks to align buildings with the carbon reduction targets set by the Paris agreement. In such procurement processes, especially within the public tender framework, projects with lower ECI values receive an imaginary discount and become more competitive in tenders (*Ecochain, 2023*). What this means is that any developer who builds with adaptability has a competitive financial advantage when bidding for contracts. Thus, by designing future-proof buildings, developers increase their chances of winning contracts, profiting from financial incentives and future-proofing their investment.

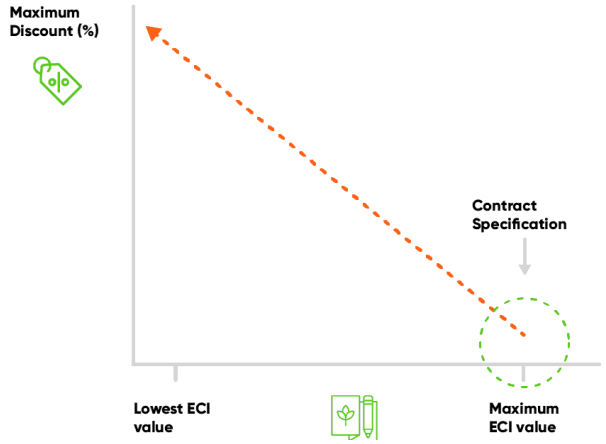

Figure 3.31: ECI reduction and Tender Advantage (Ecochain, 2023)

2. Reducing Repairing and Maintenance costs

A design that is future-proof helps minimize the compound cost of changes that take place during the use phase of a building by ensuring adaptability right from the start. During the early phases, this vision in future-proof design may be incorporated by the stakeholders with minimal financial implications.

As the project moves through the construction phase into use, changes become more costly and disruptive. Adaptability reduces operational costs, as it minimizes material waste and labour-intensive renovations, therefore allowing the building to become cheaper over time. This approach not only alleviates the financial cost on developers who must renovate their projects frequently and regularly, but it guarantees lower service fees and less noise/disturbance for tenants and owners (*Schoonwinkel et al., 2016*).

3. Inflation Hedge

A building with a longer lifespan mitigates inflation's risks in construction materials and labour. After 75-100 years, traditional buildings tend to be outdated and need expensive renovations or complete demolition and reconstruction. By contrast, a flexible 200-year building lowers its future costs over a much longer period of time by lowering the frequency of expensive reconstruction cycles.

By designing for long-term durability and adaptability, developers and investors can create stability in financial planning, prevent unpredictable cost spikes, and maintain asset value across generations. This protects the investment against material and labour cost increases, and ensures no premature demolition and reconstruction occurs, while making the building a better financial investment in the long run since it is both more secure and more resilient.

3.3.2 LCC Modules

Module A: Construction Costs

The construction costs include the material and labour required for construction the building. The materials and complexity of the construction process play a huge role in the initial financial investment. Because all configurations in this study use the same structural material, an estimation is made with a constant cost of construction.

Construction costs for apartment buildings are usually between €500 and €800 per m^3 (*Fortus, n.d.)* of the building, and this amount takes materials, labour, and MEP services into consideration. A flat rate of €700 per m^3 was selected as a baseline for this study. But this cost is affected by the height of the building, as it is based on the total volumetric footprint. The options differ in height because of varying levels of MEP services integration. Therefore, to accommodate this variation, below is the construction cost estimates applied.

Construction costs per m^2 = Costs per m^3 x height

Option	Height	Costs / m^2	Construction costs	Extra Material Costs
1	2.9	2.030	812.000	None
2	2.9	2.030	812.000	Extra embedded MEP
3	3.1	2.170	868.000	Extra foam concrete layer
4	3.2	2.240	896.000	Matrix Modules
5	3.1	2.170	868.000	None

Table 3.8: Overview Initial Construction Costs

When looking at the table of construction costs, a simple conclusion can be drawn. Buildings designed for future flexibility cost more upfront. Options 3, 4 and 5, which are the ones that are being built with future-proofing considerations, are more expensive due to larger height from lowered ceiling or raised floor systems. These systems contribute to an increase in framing height, which has a direct impact on construction costs by square meter, when each of the options use the exact same degree of main structural material.

Designs featured in both Option 1 and 2 are more cost-effective to build at the time of construction due to their simpler design and lower overall heights. However, option 2 has extra embedded MEP infrastructure, therefore being more expensive than actually visualized. The extra foam layer, and matrix modules also increase the material costs of the design, making it more expensive than traditional construction, which does not taken into account adaptability.

Module B: Refurbishment Costs

This thesis is mainly focused on the internal space plan adaptation with new approaches for enabling long term flexibility and economic viability. The building therefore has the capacity to adapt to changing market demands and social needs through the provision of reconfigurable apartment layouts. The different MEP options differ in terms of their costs on material and labour. From the LCA it was already investigated which options had a lot of material waste, this material waste goes together with high costs. Removing material requires new reconstruction material and labour which is expensive.

The relative refurbishment costs of each design option are evaluated with a comparative quantitative analysis. This method applies qualitative scores to two of the most prominent elements affecting cost, namely material quantity and labour intensity, which can vary with respect to the design strategy as it relates to MEP integration and flexibility. Each factor gets a score from 1 (very low) to 5 (very high), summing up these two values gives the total refurbishment score. This score is then simplified to cost values by multiplying by a constant (in this case 200), thus assuming a refurbishment cost index. It is an index that serves as a relative measure across the options instead of an absolute monetary amount.

$$\textit{Assumped refurbishment costs} = (Score_{Material} + Score_{Labour}) * 200$$

Due to the challenge of accessing accurate and project specific data, for the removal of housing material, reinstallation and labour regarding partial removals, a detailed cost analysis was not performed. Nonetheless, this method provides a clear and transparent framework, shown in Table 3.9, for drawing out the refurbishment consequences of each option.

Option	**Description**	**New Material Costs (Score)**	**Labour Costs (Score)**	**Assumption Refurbishment Costs**
1	MEP infrastructure embedded inside the slab	Very High (5)	Very High (5)	2.000
2	Additional MEP infrastructure embedded inside the slab	Very Low (1)	Very Low (1)	400
3	MEP infrastructure in foam concrete layer	Medium (3)	High (4)	1.400
4	Raisded floor system for MEP	Low (2)	Medium (3)	1.000
5	Suspended ceiling system for MEP	Low (2)	Low (2)	800

Table 3.9: Refurbishment Costs Assessment Framework

In Figure 3.32, a cycle is applied in which each option engages in a refurbishment cycle of 12.5 years, with a full 50-year lifespan. This assumption reflects a practical adaptation rhythm for changing the internal space plan, following the Stewart Brand model. Figure x depicts the cumulative refurbishment cost through time for each of the different structural options incorporating the assumed burden for refurbishment, as previously indicated. Calculations can be found in *Appendix I*.

- Cumulative cost increases the steepest in Option 1. Being the most intrusive in terms of economic impact since it requires extensive demolition and replacement of MEP infrastructure that is embedded in the structural slab. This leads to the most significant long-term expense over several refurbishment cycles.
- Option 3 incurs large costs as well, although lower than Option 1. Foam concrete allows for easier MEP rerouting, however its material and labour costs remain relatively high due to cutting and partial demolition required.
- Long-term performance of Option 4 and Option 5 produces considerably lower cumulative costs, illustrating the efficiency of both Option 4 and Option 5. In their design strategies, they avoid embedding MEP services into the structural slab thus ensuring minimal demolition is required.
- Incorporating MEP services in a manner that minimizes structural intervention, Option 2 has the lowest cost of refurbishing the building. This reduces retrofitting expenses considerably, although it may create some rigidity in reconfiguration.

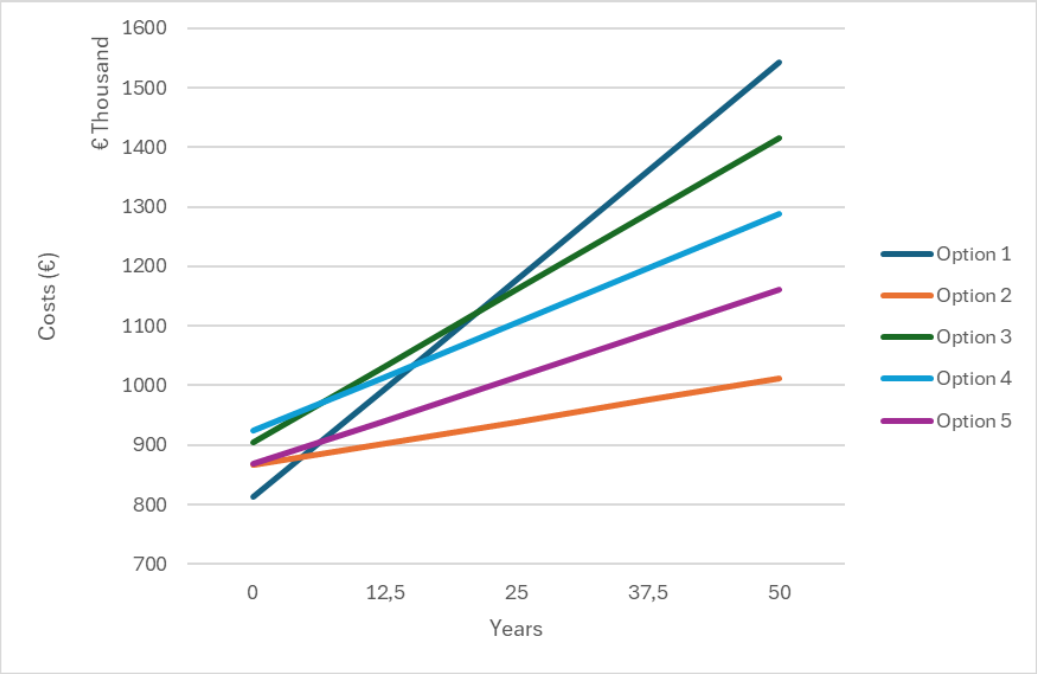

Figure 3.32: Cumulative Costs over Time

Sections above have described how the MEP can be made adaptable. The next chapter discusses why refurbishment costs should be low and how this translates to the profitability of the building. First, an example is explained that addresses the third sub question. It shows how spatial adaptability enables a building to respond to a demographic shift.

A new mid-rise residential building has been constructed in Almere (Onderwijsland, 2024). The Netherlands is currently (2025) facing an aging society, therefore the existing space plan is composed of six independent units for the elderly. Almere is currently developing plans for a new university, creating a need for student-housing. At present, each apartment is being rented for €900/month. Considering the growing demand for student housing, these units can be converted into student flats and rented for €600. However, the flexible arrangement means the existing six apartments can be reconfigured into twelve smaller ones. This allows the developer to reconfigure the apartments over time as the market readjusts, and raise its revenue with:

Change in revenue: (12 x 600) - (6 x 900) = 1800,-

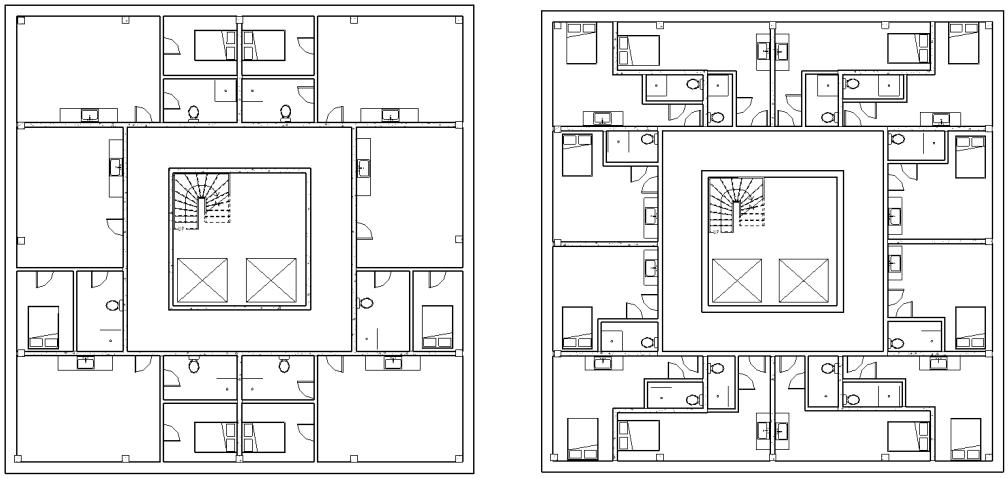

Figure 3.33: Shift from Space Plan C to Space plan D

In the methodology section, an extreme cycle was modelled where the entire space plan is transformed every 12.5 years. Although it offers informative insights into how the building adapts, this method fails to reflect most practicalities of how buildings evolve. In contrast, changes to a building's layout happen incrementally and never at stable time intervals. It is important to note that the limitation of a 12.5-year adaptation cycle offers a general framework for analysing adaptability, but the reality is more dynamic as modern demands evolve and adapt organically over time.

How quickly these adaptations happen also depends on financial limitations. As the return on substantial refurbishment investment must make sense in terms of increased rental income. Instead of reconfiguring an entire space all at once, developers are more likely to make phased refurbishments that correspond with tenant turnover (see Figure 3.34). It allows revenue generation to continue while having less impact on existing tenants.

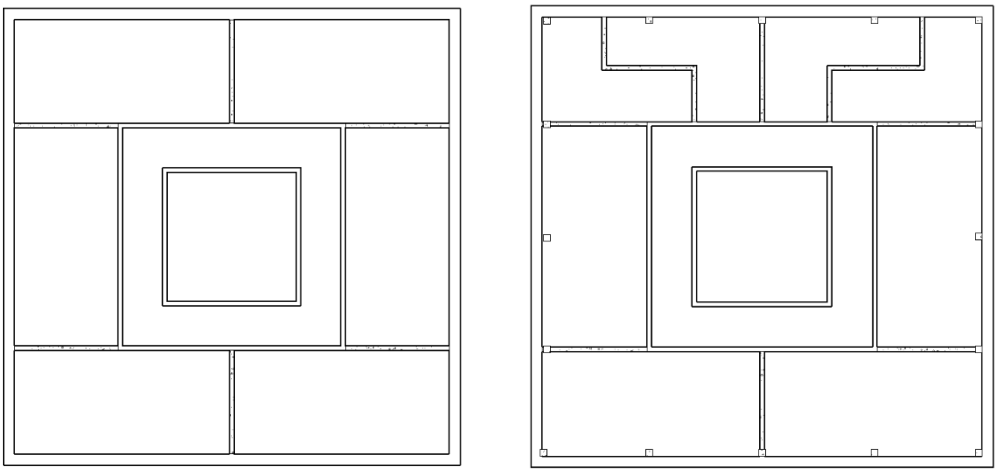

Figure 3.34: Phased Refurbishment Approach

Changes are forced to happen when the market demands needs it and not on a fixed period. The adaptation cycle is not maximally rigid, so several factors including tenant demand, occupancy rates, and economic factors often lead to reconfigured apartments. Therefore, a more realistic situation can be calculated with the following formula:

$$A_t = (\sum^T (R_t - R_0)) - C_t$$

Where : $(\sum^T (R_t - R_0)$ *= the sum of rental income profit change over time T*

C_t *= cost of refurbishing the apartment*

A_t *= adaptation feasibility (if* $A_t > 1$ *, adaptation is profitable)*

Option 2, 4 and 5 decrease the cost of refurbishment (C_t), which is used in the adaptation formula, in a considerable way as it is less required to adjust the structure and the mechanical, electrical and plumbing (MEP) solutions. The arrangement of MEP systems outside the slab versus embedded, which lessens adaptability costs. The other MEP design, where MEP infrastructure is included in the slab, requires high amounts of demolition and reconstruction to reroute utilities and add new layouts. Ensuring these systems remain accessible, and separate from the structural components allow for any necessary updates to be made with minimal disruption.

Lowering the cost C_t improves the adaptation feasibility A_t, therefore the configuration not only shows the environmental and economic impact, but also increases the building's long-term profitability. This means that adaptability not only serves the sustainability strategy but also results in a profitable real estate development. This allows the configuration to stay ahead, keeping financial risk low while maximizing the asset value potential over time.

Module C: End-of Life Costs

Lifespan Assumption Model

In terms of Life Cycle Cost (LCC), in the end-of-life stage, the demolition costs are usually just a minor component. Small differences in floor height, or other material volumes make little impact on the total destruction cost of a building. The real financial impact of Module C, however, is tied to the lifespan of the building itself.

Buildings which exhibit limited adaptability inevitably get demolished early, not due to structural failure but because their configurations or systems cannot be easily accessed or reconfigured. It initiates a whole new reconstruction cycle, resetting material costs, labour, and further price inflation. So just like the LCA, the reason Module C matters isn't about how expensive demolition is, but rather about when demolition takes place. The options that postpone or eliminate end-of-life replacement are less frequently reconstructed, reducing both LCC and embodied carbon. Such end-of-life thinking is essential to a future-proof, sustainable, and financially sound approach to buildings. In order to assess long-term economic feasibility, the lifespan assumption model was applied to estimate the Life Cycle Cost (LCC) of the different options. This builds on the assumptions established in Module B of the LCA, but now includes the complete reconstruction cycles of each design option over a 300-year life. Calculations form the worst-, mid- and best case scenario can be found in *Appendices J-L*.

	Worst case	**Mid Case**	**Best Case**
Option 1	50	75	100
Option 2	50	75	100
Option 3	75	100	200
Option 4	200	250	300
Option 5	200	250	300

Table 3.10: Lifespan Assumption Model

The results for the worst case scenario can be seen in Figure 3.35 on the next page. The sharp jumps in the graphs represent new reconstruction cycles, where the whole building is demolished and completely rebuilt after continued failures or inaccessibility of the MEP system. By contrast, reconfigurable configurations are much less expensive over time. Alternatives that support continuous internal adaptations without forcing complete replacements retain a flatter cost curve.

Even though Option 2 was the most financially viable in terms of short-term refurbishment (Module B), the performance is reduced considerably when looking over several generations. In comparison, Options 4 and 5, due to the fully open and accessible spatial service zones, operate with less reconstruction and lower cumulative costs over their life cycles.

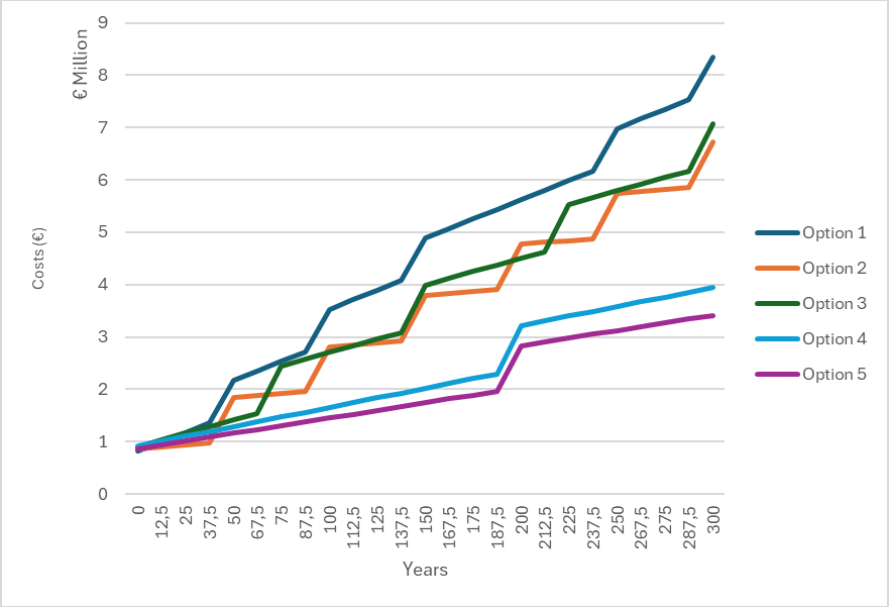

Figure 3.35: Cumulative Costs Worst-Case

The mid-case scenario indicates fewer full reconstructions than the worst-case, leading to a smaller divergence between the total accumulated costs for the options over time compared to the last analysis. Though still the most expensive option overall because of its rigid embedded MEP layout and excess refurbishment costs, the financial spread between options is much closer. Because of large demolition rates in the past, Option 2 did not perform well according to the latest generation, but it was mid-case competitive and becomes gradually more competitive over time. This method still has (generally minor) spikes in cost jumps but overall represents the lower portion of Option 3 costs due to a nominally longer service life.

Options 4 and 5 prove to be the most stable and least costly over time. This demonstrates the cost advantage of having fewer reconstruction cycles up front and having more linear and in many cases flat cost development. While the initial implementation cost of each of these designs can be higher than other proposed designs, it offers greater longevity over time and is consistently the best design choice for controlling life cycle costs.

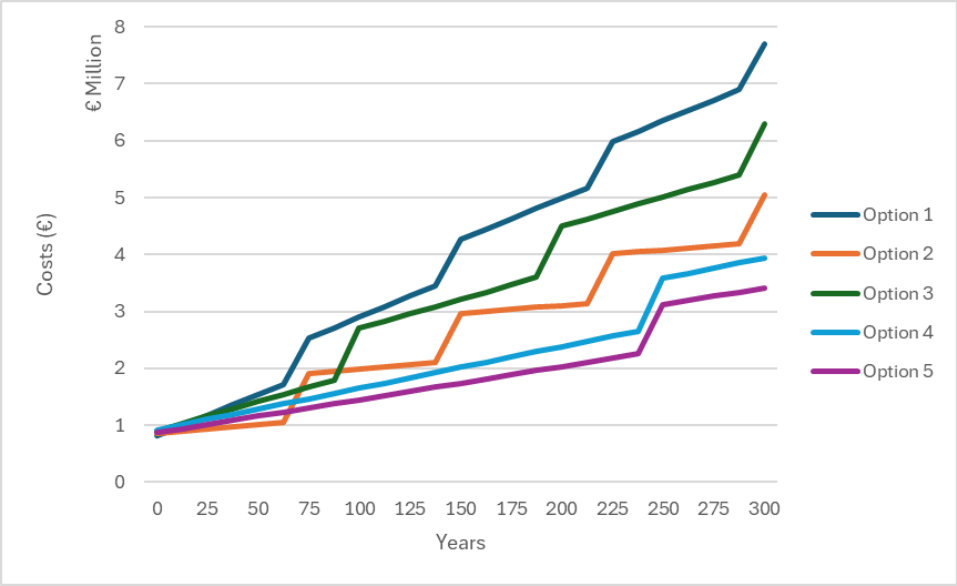

Figure 3.36: Cumulative Costs Mid-Case

In the best of cases, performed on the next page, where the MEP systems are designed to perform well and no premature failures occur, the differences between the options characteristically shift. The overall total costs are found to be lower due to fewer reconstruction cycles. However, the long-term financial feasibility of any given design becomes more reliant on its refurbishment efficiency, and embedded adaptability.

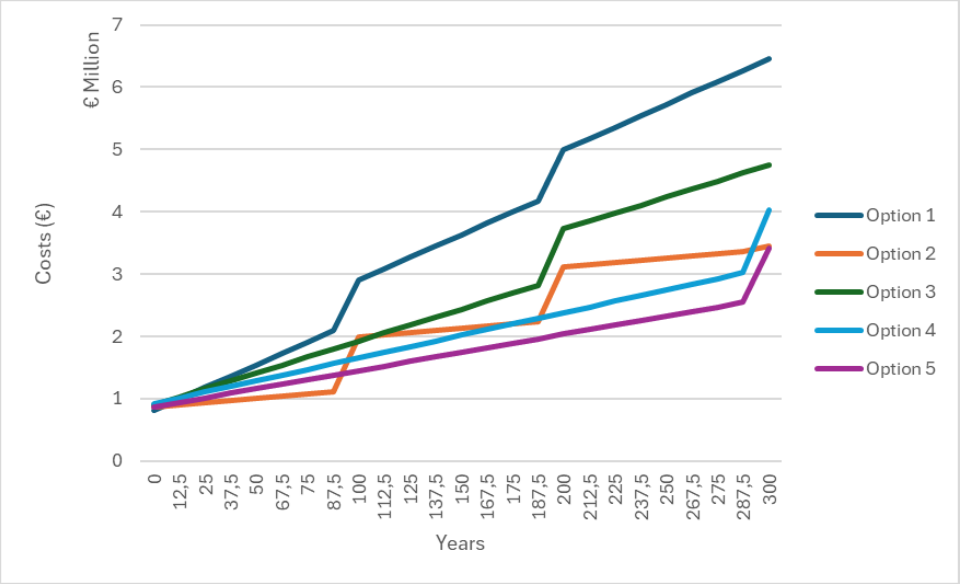

Figure 3.37: Cumulative Costs Best-Case

Option 2 shows a significant improvement under these best-case assumptions. Because service zones are planned at an early stage of slab design, this option avoids the costly demolitions. Since the services are embedded, but their routes are pre-fixed and secured, refurbishment work is less invasive and more cost-efficient. Option 2 now outperforms Option 4, due to its low refurbishment costs. The most economical solution remains Option 5. The suspended ceiling system meana that they interfere minimally with structures as they are refurbished, and also allow layouts to be easily reconfigured.

In the end, the study shows that future-proof building concepts are slightly more expensive in the beginning but productive in the long run. Such stratified structures not only limit the frequency of reconstruction and thus serve as a hedge against inflation or material price volatility.

3.3.3 Inflation

Since the lifespan is considered over centuries, Module C of the study needs to consider inflation. In the Life Cycle Cost (LCC) aspect, inflation is essential because it increases the costs of construction, refurbishment, and demolition in the future. Without including inflation, future costs are assessed at lower values, resulting in underestimated costs. The annual inflation rate used in this study is set at 2% which is representative of the long-term historical average (*bbn adviseurs, 2024)*. The future value of construction and refurbishment costs is therefore affected by:

$$\textbf{\textit{Future costs: } FC = C \times (1 + i)^t}$$

Where C: initial construction

t = time (years)

I = inflation rate (%)

The structural core of a building which is built to stand for multiple generations, becomes an inflation hedge. Other building elements, like MEP systems, finishes, and façades, need to be periodically replaced and face an increasing cost trend over time due to inflation. The retained structure escapes these recurring expenditures. Now it is possible to assess the LCC assumptions over all the options. In the table the worst-case scenario of the LCA is shown, with its reconstruction cycle over 200 years. The worst-case is chosen for the assessment based on inflation.

	Lifespan	**Reconstruction cycle over 200 years**	**Inflation impact**
Option 1	50	3x	At year 50: 2.69 At year 100: 7.24 At year 150: 19.49
Option 2	50	3x	At year 50: 2.69 At year 100: 7.24 At year 150: 19.49
Option 3	75	2x	At year 75: 4.42 At year 150: 19.49
Option 4	200	0x	-
Option 5	200	0x	-

Table 3.11: Inflation Effect on Long-Term Costs

While future revenues see their own gradual increase (and the precise profitability of this business model is difficult to quantify), the retention of the load-bearing structure of the building offers an immense financial benefit. The analysis is limited to the reinforced concrete structure, which generally contributes a major share of the initial construction cost. The replacement cycles are assumed to have similar costs over each cycle for MEP systems, interior layouts, and finishes based on the study, wherein the renovation is performed for non-structural layers. However, by keeping the load-bearing structure intact, all costs related to structural removal, reconstruction or material procurement are avoided.

Option 1 and Option 2 have similar 50-year life spans, which means three full reconstruction cycles in a 200-year period are needed. These cycles occur at years 50, 100, and 150, when inflation is input at an annual rate of 2% and construction costs are multiplied respectively by factors of 2.69, 7.24, and 19.49. This means the core will be 2.69 times more expensive to build in 50 years, and almost 20 times more expensive in 150 years.

Option 3, with a service life of 75 years, needs to undergo two reconstruction cycles over 200 years. They happen at years 75 and 150, with inflation multipliers of 4.42 and 19.49, respectively. However, in contrast to options 1 and 2, significantly fewer reconstructions are required, although at a time in which the inflation effect is again high in the second cycle.

Options 4 and 5 are intended to last and maintain the structural system in place over the full 200-year timeline, or even longer. Consequently, major structural reconstructions are not needed, and inflation effects are completely nullified for these options. This illustrates an important benefit of future-proof buildings: whenever costly renewals for the structure are avoided, long-term savings is realized and inflationary pressure is reduced.

3.4 Expansion

The previous analysis looked at the LCC and LCA at the floor level to give insight on how different structural configurations affect environmental and economic performance. But buildings are designed and, of course, operate as integrated systems, so a floor-level assessment in isolation underrepresents the totality of long-term costs and benefits.

3.4.1 Floor-to-Building Level Analysis

When scaling up from an analysis at the floor level to the full-building level, some structural factors do not scale linearly. As building height increases, the load-bearing structure requires more material, resulting in greater environmental and economic impacts. Lower floors must bear the accumulated weight of upper levels, resulting in thicker columns, stronger cores and larger foundations, sharply increasing embodied carbon emissions and construction costs. With more material needed than is minimized through a rational use, non-linear growth leads to higher reinforcement ratios and more resource extraction, resulting in higher costs and environment impacts. However, this impact applies to all load-bearing configurations, and are therefore not important to investigate for this research. What is important to note, however, is that as the building scales up Configuration 4 needs to stay fulfil the requirements set. Going up in height, comes with additional structural complexities. Below the impact per layer is explained as the building increases in height.

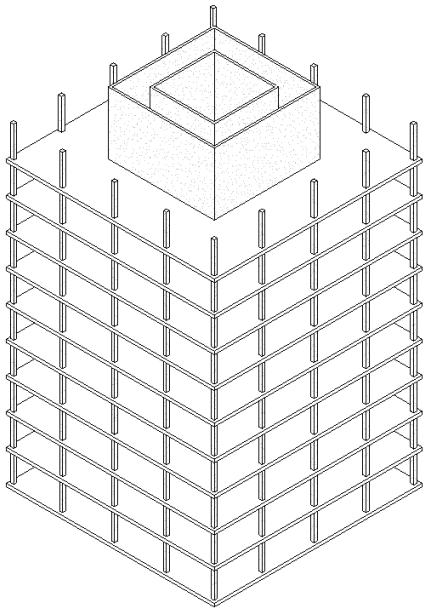

Figure 3.38: Core-Based Column Structure – Configuration 4

Layer	**Impact on Load-Bearing Structure**
Structure	Affects directly materialisation and amount; tall buildings demand more robust foundations, bigger columns and tighter cores
Services	MEP systems and elevators dictate the size of the core and shafts, which reduces flexibility in the building's load-bearing structure and needs dedicated vertical space. The more services, the bigger the core.
Skin	The weight of the façade and wind loads determine lateral stability and often lead to the need for additional bracing or a stiffer structural core in buildings with greater height.
Space Plan	Grid for column and location for load-bearing walls must be made accounting for adaptability. When building taller, structural efficiency becomes more critical.

Table 3.12: Structural Layer Impact Expansion

As the scale of the building increases, more material is needed, resulting in thicker columns, stronger cores, and larger foundations to bear the increasing loads. However, increasing the height of the building has no impact on its longevity, as long as the same requirements are met from the literature study.

Taller buildings should therefore be structurally sound while retaining adaptability, flexibility and usability of the building for the long run. As with Configuration 4, allowances are made for column, slab, and core thickness variations necessary for structural integrity, but the space plan itself cannot change. To accomplish this, the following constraints need to hold:

- *As height increases, the structure cannot require a space plan which requires internal columns or load-bearing walls, as this inhibits adaptability.*
- *As height increases, the structure cannot require additional bracing that limits façade flexibility, reducing the ability to replace or upgrade exterior elements.*

Structural optimizations for stability requirements at greater heights are outside the scope of this research. Although materialization, core design, or reinforcement strategies might need to be adjusted for taller buildings, these optimizations are irrelevant to the paper's main focus on adaptability and longevity, since they're not affected by the increasing height.

More important to investigate is the difference in total height over the MEP options. While these height differences may seem minor from floor-to-floor, over an entire multi-storey building they do add up. For example, both Options 1 and 2 have a total height of 58 meters across 20 floors, while Options 3, 4 and 5 range from 62 to 64 meters, up to 6 meters taller. This extra height is not a defect, but rather an intentionally allocated space for service zones, the flexibility in the space plan, and long-term operational maintenance access.

Designing for future-proofing therefore demands slightly higher floor-to-floor dimensions, but this target is a trade-off that supports buildings that can adapt to changing user demands, can be reconfigured without demolition and can remain standing structurally intact for generations. Extra height for ceiling should be seen as an architectural and operational investment in the durability of the structure, not an inefficiency.

	Floor-to-floor height (m)	**Floors**	**Total height (m)**
Option 1	2.9	20	58
Option 2	2.9	20	58
Option 3	3.1	20	62
Option 4	3.2	20	64
Option 5	3.1	20	62

Table 3.13: Total Building Height across MEP options

3.4.2 Vertical Expansion

When developers construct a building, the total height of a building is determined by the economic balance between revenue and construction costs (*Chau, Wong, Yau, & Cheung, 2007*). Developers aim to maximize profit, which is the difference between total revenue and total costs. In formula this can be written as:

$$Profit\ (P) = Revenue(R) - Costs\ (C)$$

Revenue is earned by (in this case) renting the usable space, while the costs come from the construction and land expenses. Developers continue to add floors as long as the revenue from an additional floor is greater than its construction cost. When at a certain height the costs of adding floors become too high, the optimal height is reached. At the optimal height therefore the following equation applies:

$$At\ Optimal\ Height\ (H^*):\ Profit\ (P) = Costs\ (C)$$

Market conditions change over time, impacting revenue (R) and costs (C) leading to differences in the profitability (P) of a building. If demand for more space increases, a structure that was optimal from an economic standpoint at its original height may well fall underutilized. The vertical expansion of existing buildings becomes a financially sound alternative when several factors , such as population growth, urban densification and real estate value increases occur.

Revenue (R) is directly correlated with market demand, so new floor additions could earn more than originally projected as property values and rental income increase. On the other hand, construction costs (C) vary over time and are affected by inflation and the availability of materials and labour. If rental prices are growing even faster than construction costs, vertical expansion becomes very attractive for a developer. Therefore, the optimal height (H*) can change over time.

The building itself is designed to respond to social needs within its existing footprint, so that apartments can be reconfigured in terms of their layout and space allocation over the years. But for vertical adaptation, the structure must physically grow upward to accommodate heightened demand for space, which is a different challenge.

A consideration of creating a future-proof building is ensuring potential vertical expansion through the load-bearing structure. Although this does not mention any additional structural requirements to be in place to allow growth vertically, it could be something to consider in the design of the load-bearing structure.

The foundation and core can be sized to accommodate future loads without extensive retrofitting. This involves making sure that the original structural system is capable of carrying extra weight. Additionally, the roof can be designed as a modular, non-load-bearing component that can be easily detached and expanded without major reconstruction.

Design for vertical expansion is an aspect of a future proof-building, and therefore worth noting. However, it is a design strategy, not a structural requirement. Designing a load-bearing structure with future vertical addition capabilities demands even more material used in the foundation and core, which in turn makes the structural economic and environmental impact significantly higher from the beginning. Of course, this comes at the cost of increasing the initial complexity, which should be balanced out against the building's long-term flexibility and lifespan.

Vertical expansion does not become impossible with future refurbishments if not considered in the initial design, but it does make refurbishments more complex and expensive. Typically, retrofitting a structure to accommodate new floors involves reinforcing existing load-bearing elements, upgrading foundations, resulting in higher construction costs, extended project timelines and more material waste. Therefore this strategy is something which could be considered, but should not be a requirement.

3.4.3 Horizontal Expansion

Expansion is not limited only to the internal layout and site plan, buildings can be added horizontally, integrating themselves with potential market opportunities. By using this method, the building can expand its usable area without significant structural changes. In contrast, horizontal expansion builds a whole new section that has its own foundation, so the ability of the foundation and structural system to bear new loads is irrelevant, although integration with the existing building is important.

When designing a building, especially in urban settings where every square meter is carefully planned (there’s rarely any wasted space), horizontal expansion isn’t something developers usually take into account in the initial vision. The surroundings may be built up by the time of its development, hindering any immediate action for expansion. But as the years go by, changes to land use do occur, and new growth opportunities may arise. Buildings in the area, may be torn down, refurbished or left empty so they can expand in a way they previously could not.

In these situations, a building that has already considered options for horizontal growth can offer a major strategic and financial advantage. Two key design elements, which the design configuration possesses, help make this possible. First, the adaptability of the skin layer, the façade is modular and can be reconfigured as needed. It allows for an additional wing to be added to the original structure with minimal retrofitting. Because MEP services can be located below the slab in a new section, these systems can easily extend into the new portion with

minimal disruption to existing systems. All new installations are able to connect at the planned expansion points without costly relocations or infrastructure upgrades. The requirements set in this thesis not only remain for the longevity of the structure itself, but it also gives the possibility to expand horizontally.

Horizontal expansion could necessitate the internal placement of columns, running counter to one of the original requirements of an open space plan, which gives as much flexibility as possible. The first design minimized load-bearing components to allow versatile spatial arrangements. However, if a new wing is being added, it might not be structurally possible to keep entirely open spans, especially if the addition requires large unsupported areas. This adds an element in the decision making process where the presence of internal columns must be balanced against the flexibility of the space plan.

3.5 Results and Discussion

The results of the research and its interpretation are presented in this chapter, where the environmental and economic impacts associated with the adaptation strategies in mid-rise residential buildings are analysed. These results are based on Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) analysis of the performance of various structural configurations over an estimated 200-300 year lifespan. The findings are addressed with regard to the research question:

How can the primary load-bearing structure of mid-rise residential buildings be designed to be both sustainable and future-proof in order to avoid demolition?

The results of the LCA and LCC are consistent with the Stewart Brand model, which describes the longevity of buildings involving elements with different life spans and adaptation cycles. However, first a quantitative analysis has been carried out to assess different load-bearing structures, which are in line with the open building philosophy and Stewart Brand model.

3.5.1 Results Quantitative Analysis

The first part of the methodology selected Configuration 4 as the best design based on adaptability assessment. The future-proof load-bearing design should require:

- A completely open space plan at ground level, which is made possible through the elimination of load-bearing walls and internal columns, maximizing flexibility and providing a greater variety of space plan configurations.
- A two-way slab system which allows for an unobstructed ceiling design, as loads are transferred in two perpendicular directions, removing additional beams.
- Flexibility of the skin layer which does not affect new apartment configurations, load-bearing walls should be removed and only columns should be used.
- In ascending height, the structure must exclude interior columns, load-bearing walls, and constraining bracing, thus preserving space for adaptability and façade flexibility.

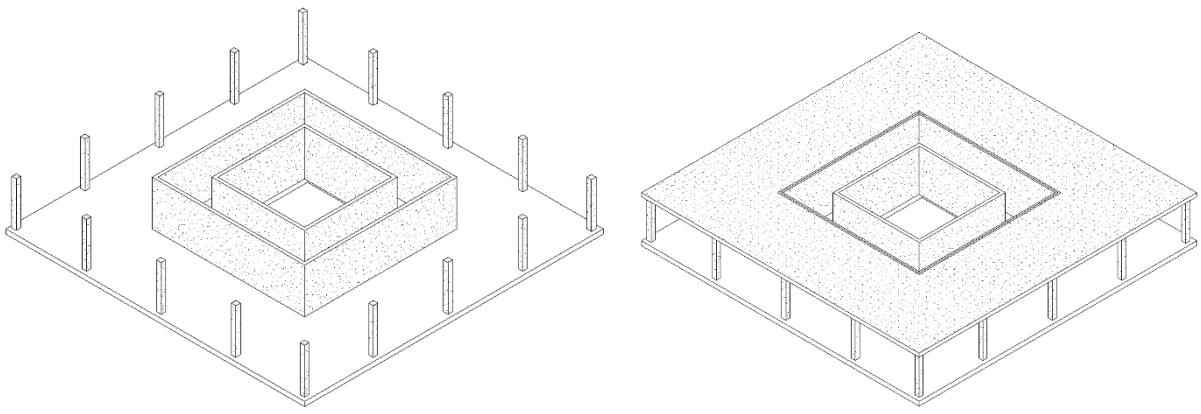

Figure 3.39: Configuration 4

3.5.2 Results LCA

With the structure layer selected, the LCA and LCC focused on investigating a new MEP design compared to traditional approaches with the goal of expanding the lifecycle of a building. The LCA results (Figure 3.14) showcase the environmental impact of different MEP configurations summed over three modules of the construction cycle based on total carbon emitted annually. The results are highlighted under a worst-, mid- and best-case scenario. These scenarios are all related to different lifespans of the building, therefore impacting annual emissions. Solutions which use out-of-slab methods (raised floor systems and suspended ceilings) vs inside-slab solutions decrease embodied carbon by:

- 69% in the worst-case
- 60% in the mid-case
- 54% in the best-case

	Worst Case	**Mid Case**	**Best Case**
Option 1	1142	1129	973
Option 2	1063	708	531
Option 3	954	752	449
Option 4	374	341	284
Option 5	248	198	165

Table 3.14: Annual Emissions Results

Option 1 is provided for comparison, but it is impractical in real-world applications. It serves to highlight the limitations of traditional MEP design. The high emissions across the scenarios point to the fact that traditional approaches are inherently not adaptable enough to future proof buildings for space plan changes and MEP maintenance.

When it comes to the practical solutions, Option 5 comes out on top against all others, resulting in the lowest carbon emissions across the board. Option 4 as well performs strongly, particularly against more solid and established arrangements like Options 2 and 3. The out-of-slab options result in an average 61% decrease in emissions compared to solutions which are embedded inside the slab. This could even be further reduced if the material of the building reaches its maximum design potential of 500 years.

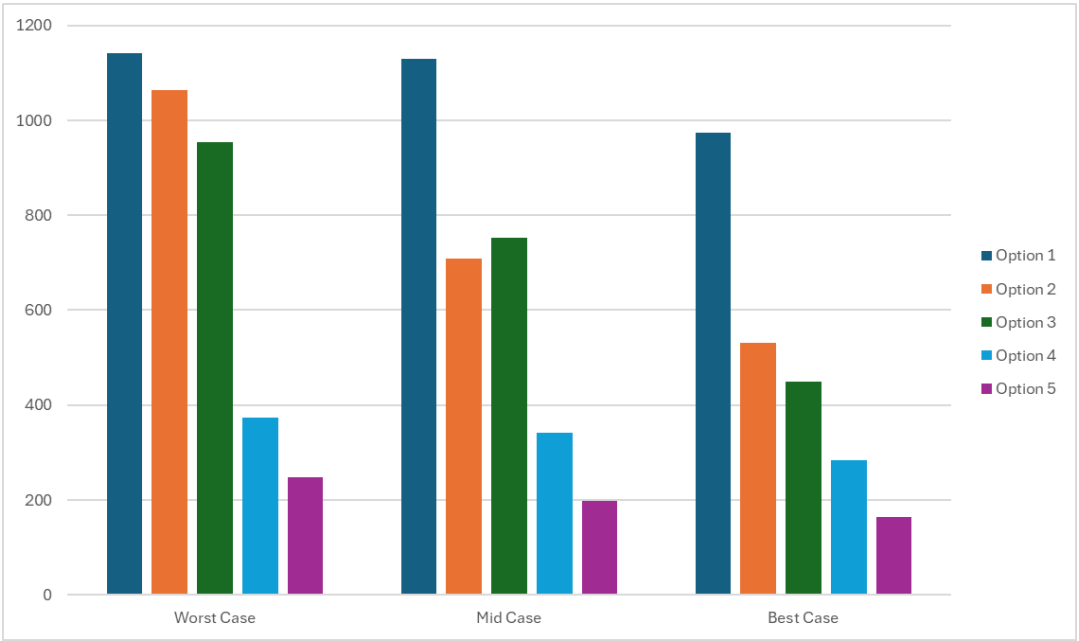

Figure 3.40: Comparison of Annual Carbon Emissions

3.5.3 Results LCC

The LCC analysis proves that in order to reach greater adaptability, the buildings must be built at a higher cost for their initial construction, requiring more components and systems (Module A). In fact, once one includes refurbishment and renovation costs (Module B) in the assessment, these flexible variants become more attractive from an economic standpoint. While traditional configurations might appear cheaper at first glance, they become a lot costlier when upgrading to new space plan layouts, due to their inflexibility. Investing in adaptable systems yields lower lifecycle costs and aligns with long-term, future-proof building strategies.

Option	**Initial Construction costs**	**Extra Material Costs**	**New Material Costs**	**Labour Costs**
1	812.000	None	Very High (5)	Very High (5)
2	812.000	Extra embedded MEP	Very Low (1)	Very Low (1)
3	868.000	Extra foam concrete layer	Medium (3)	High (4)
4	896.000	Matrix Modules	Low (2)	Medium (3)
5	868.000	None	Low (2)	Low (2)

Table 3.15: LCC Cost Breakdown

Module C takes into account replacement costs and reconstruction cycles over a 300-year time span, considered worst-case, mid-case and best-case. The financial advantage for adaptable options is evident in the worst-case scenario, selecting Option 4 and Option 5 as the most financially viable option. However, as scenarios improve toward the best-case, the differences across the options become smaller. Option 2 outperforms Option 4 due to its low replacement costs. From this analysis it can be concluded that the number of reconstruction cycles is the main driver for long-term cost-efficiency.

3.5.4 Discussion

The results confirm what similar studies in the literature expect from LCA. The literature study indicated that renovating a building can drastically reduce carbon emissions compared to demolition and reconstruction. Multiple studies (*Van Grunsven, 2023; Woonbond, 2023*) showed that carbon emission can be reduced with renovation instead of demolition.

The LCA results are consistent with existing research on how adding longevity affects carbon savings. Buildings with a lifespan over centuries have lower annual emissions than buildings designed for a few decades. These findings reinforce the already well-established concept that extending the life of a building is the single most effective means of decreasing embodied carbon. While the study is not directly addressing refurbishment strategies, it makes a clear case that longevity leads to fewer carbon emissions. Because life cycle assessment (LCA) accounts for the environmental impact of longevity, the findings strongly promote refurbishment as a central approach for prolonging building use and reducing emissions associated with demolition.

Previous research on renovation and refurbishment has not accounted for different MEP configurations as a variable. This study adds to established literature by introducing the topic of MEP adaptability into the debate about how different structures can enable longevity and ultimately carbon reductions. Thus, this study provides a new approach to the influence of structural design decisions on long-term sustainability by incorporating adaptability into LCA.

There remains ongoing debate regarding the financial implications of designing for longevity and reducing demolition, as existing literature identifies gaps in cost analysis. The cost of renovating a building versus demolishing it differs between all projects. It is dependent on multiple factors which are hard to generalize. Some buildings are cheaper to renovate and others are cheaper to demolish and reconstruct. The results of this study show that extending the lifespan of the load-bearing structure alone can be economically viable, yet this does not consider financial impacts derived from renovation strategies and maintenance needs. The actual long-term cost-benefits of preventing such demolitions via design investments that incorporate durability would have required further examination of renovation costs.

This research aims to change construction stakeholders' general approach to the design of load-bearing structures, recommending a lifespan of over 200 years for future buildings, to meet sustainability targets. This extended time frame enables future generations to enjoy resilient, low-carbon, and economically viable buildings at much less of an environmental and economic cost associated with demolishing and rebuilding. Integrating adaptability within the structural design allows a building to evolve over time while retaining its load-bearing structure.

This research supports this theoretical implication by demonstrating that MEP adaptivity is a key to prolonging the building long-term performance while decreasing embodied carbon emissions and life cycle costs. More research is needed to validate these findings, enhancing the adaptability modelling and the investigation of material innovations to maximize flexibility and resource efficiency. This study lays the groundwork for further research on how metrics of adaptability might be integrated into sustainability standards, policy frameworks, and economic feasibility analyses.

Although this study has generated certain significant findings, it is important to highlight some limitations, as is demonstrated in the forthcoming chapter. In the concluding section, practical implications of the findings are discussed, and the recommendations for developers, policymakers and the construction industry are explored.

3.6 Limitations

The study in this paper lays a solid groundwork for how longevity impacts sustainability and cost efficiency. However, some limitations must be acknowledged. The importance of such limitations helps to put the findings into context and emphasizes the need to conduct future research focused on other materials and more realistic refurbishment models.

Space Plan Changes

In order to evaluate the implications of longevity and adaptability, this paper introduced some extreme space plan changes, where layouts are assumed to be altered every 12.5 years. This exaggeration provides a way of quantifying the benefits of the different configurations, but it does not necessarily capture real life refurbishment trends that take place in response to market conditions. Nonetheless, as the same assumptions govern all configurations, it does not change the relative outcome but rather emphasizes the differences between them. The analysis still clearly identifies Option 4 and 5 as the most sustainable long-term solution.

Material Selection

This study focuses on reinforced concrete as the load-bearing material under the assumption that it continues to prevail in mid-rise residential construction. Advances in materials, including bio-based composites and engineered timber, as well as low-carbon concrete, are also laying the foundation for both structural adaptability and improved environmental performance. Engineering through the use of these materials could lead to more eco-friendly construction models thereby resulting in lower embodied carbon emissions through circular construction principles.

This study is limited in that it does not consider other load-bearing designs that could be more advantageous for other materials. As an example, timber structures might require a different structural system (a beam system with higher material usage for load bearing capacity). The fact that a material-efficient approach designed around the special properties of timber or other sustainable options can potentially have a lower overall environmental impact compared to typical reinforced concrete construction. The use of prefabricated modular elements could also lead to lower emissions in the construction phase of the building (Module A).

A key issue relates to the use of cement in reinforced concrete structures, whose production remains one of the most significant contributors to global CO_2 emissions. Although this study examined how second life added to the consideration of adaptability in reducing life cycle emissions, it did not factor in alternative concrete formulations (for e.g. geopolymer concrete, cement-free binders, or recycled aggregates) that could enhance environmental performance. Further research is needed into the implications of alternative structural materials and associated design adaptations on both longevity and total life cycle emissions.

Height Constraints

Also, the study sets the maximum building height at 70 meters, in line with current mid-rise building guidelines. Urban land, however is becoming a premium, and buildings are forecast to rise to ensure greater population density and land use efficiency. Depending on the type of building and the height, the shift can have a significant impact on the selection of the load-bearing structure as tall buildings require a different design approach in terms of constructability, and structural stiffness, wind resistance, core design, etc. Only with substantial alterations can the open-space structural type examined in this study, be scaled to high-rise construction. In high-rise development, future research should examine if a such load-bearing design with an open space plan is feasible.

Regulatory Constraints

The study does not consider the governing regulations and legal requirements involving mechanical, electrical, and plumbing (MEP) services within multi-unit residential buildings in the Netherlands. The MEP installations, according to the Bouwbesluit 2012 and other applicable regulations, cannot cross from one apartment to the another without meeting stringent requirements that are related to fire safety, acoustic insulation, ownership, as well as management. In a homeowners' association governed building, each one of its units must have independent controls with its own access to important shut-off points for gas, water, and electricity utility services. Furthermore, since Option 5 of the MEP design focuses on constructing MEP services outside of the slab, wastewater drainage and ventilation ducts must be routed through shared spaces, rather than private residential areas, which does not comply with fire compartmentalization and soundproofing regulations.

As this study is primarily focused on structural flexibility and long-term cost-effectiveness, it does not consider these regulatory limitations on the placement of MEP systems. In reality, the legal and technical constraints of building services might be the determining factors of whether flexible space planning and phased renovations are beneficial or even possible.

4. Conclusion and Recommendations

The findings of this study show that extending a building's life can cut environmental impact, supporting the need for designing for longevity. Adaptable structures can help to prevent needless demolition cycles, minimizing material wastage and carbon emissions. This underscores the importance of policymakers in fostering future-proof construction principles via incentives and regulatory frameworks.

4.1 Scientific Relevance

This research contributes to the understanding of structural resilience and adaptability for sustainable building design by incorporating these qualities into the quantitative life cycle analyses. Although prior studies have provided a substantial focus on operational efficiency and renovation practices, little research has acted upon the alternative MEP configurations in relation to their long-term environmental and economic performance. Using LCA and LCC as tools, this research quantifies the benefits of adaptable structural systems through data-driven evidence, proving their capacity to mitigate embodied carbon emissions and life cycle costs across long-term timeframes.

This study emphasizes the strategic location of MEP infrastructure outside the structural slab, pointing in the direction of long-term design adaptability. This LCA approach demonstrated the most distinct environmental benefits throughout. Options with MEP outside the slab (Options 4 and 5) exhibited up to 61% lower annual carbon emissions than typical slab-embedded MEP systems. These designs also performed significantly better in more optimistic scenarios, demonstrating their robustness against demolition decisions.

Adaptive construction strategies in Module A may have been found to be potentially more costly to implement, because of both the materials used and the height of the structures. However, over long periods, due to more accessible and flexible infrastructure, it became evident that these upfront expenditures led to lower costs over the long-term. Significantly, Option 2 with extra MEP infrastructure embedded from inception emerged as one of the most cost-effective solutions in the best scenario. However, the out-of-slab options appeared as the most cost-effective approach across all scenarios.

These findings contribute to a basis for future recommendations and industry practice, further advocating not only for modular design, but also for an explicit inclusion of longevity and adaptability into early-stage design. The findings from this research can feed back into building codes, sustainability approvals, and investment strategies, so that the buildings of the future are not only environmentally more sustainable, but also financially more viable.

4.2 Societal Relevance and Practical Implications

This research contributes to long-term resilience in the built environment by improving societal impact. As urban areas expand and land gets scarcer, buildings need to be functional and flexible from one generation to the next. This study addresses the key concern of how buildings can be designed to be future-proof and sustainable without the need for demolition.

Adapting well to changing needs and preferences by integrating options for flexibility in living spaces, buildings can adjust as families grow and evolve in house sizes, preferences, and lifestyles. When structures remain standing and change to accommodate societal needs, people are less likely to have to move out of the area, and social networks are less likely to be disrupted, leading to healthier long-term community ties.

This research emphasizes the importance of designing load-bearing structures to facilitate adaptability to changing housing needs and reduce demolition. Its findings are relevant to developers, architects, engineers, policymakers, and urban planners. The table below summarises the main stakeholders and their role in the construction of future-proof buildings.

Stakeholder	**Role in future-proof Construction**
Developers	Invest in buildings that will be flexible, even if construction costs are higher on the front end, to maintain long-term value in an ever-changing marketplace while minimizing the risk of vacancy. Flexible design improves ECI score, makes tender more attractive, and results in Paris Proof compliance.
Architects	Use open layouts with similar spacings throughout, allowing for easy internal reconfiguration without extensive structural work. Design higher building with out-of-slab MEP options.
Engineers	Design new load-bearing approaches that enable reconfiguration of spaces via the elimination of structural elements, promoting an open space plan.
Policy makers	Encourage adaptable construction, ensuring buildings reflect future needs through regulation (e.g. changing Bouwbesluit regulations), financial incentives, and sustainability standards, which lead to long-term resilience in the built environment.
Urban Planners	Develop and integrate real strategies for long-term future-proofing urban planning. Focus on buildings that can change over time to meet evolving needs of the community to minimise vacancy and obsolescence as local areas change.

Table 4.1: Stakeholder Recommendations

4.3 Recommendation for Future Studies

Although this study offers valuable perspectives of providing load-bearing structures with MEP options that support future adaptation, many fields remain to be further explored to deepen the empirical and practical basis of constructing future-proof buildings.

Research should aim to find alternative materials that could last for two centuries without losing structural integrity. This study is focused on reinforced concrete, future studies should consider investigating the long-term durability of engineered timber, bio-based composites, modular prefabrication, and low-carbon concrete.

Future research should look into methods of positioning MEP services outside the slab since in-slab installation limits adjustability of the building. Alternative routing methods, such as suspended ceilings and raised flooring contribute towards flexibility as well as maintenance and accessibility, and compliance with building regulations. Reconfigured MEP systems allow spaces to be repurposed without the need for invasive works to the load-bearing structure.

However, adaptability can also go one step further, rather than simply designing a load-bearing system for a building that is flexible. One could consider how the design of flexible walls for the interior of a building goes beyond this behaviour. At a more urban scale, research into modular partitions and reconfigurable layouts could further maximize a building's potential to adapt to varying user needs. Besides, strategies for vertical or horizontal expansion can be investigated, making it possible for buildings to physically grow in response to future spatial needs.

Filling these gaps provides the foundation for future investigations that will improve adaptability strategies, enabling buildings to remain functional and sustainable for future generations.

Appendices

Appendix A: Space Plan Variations

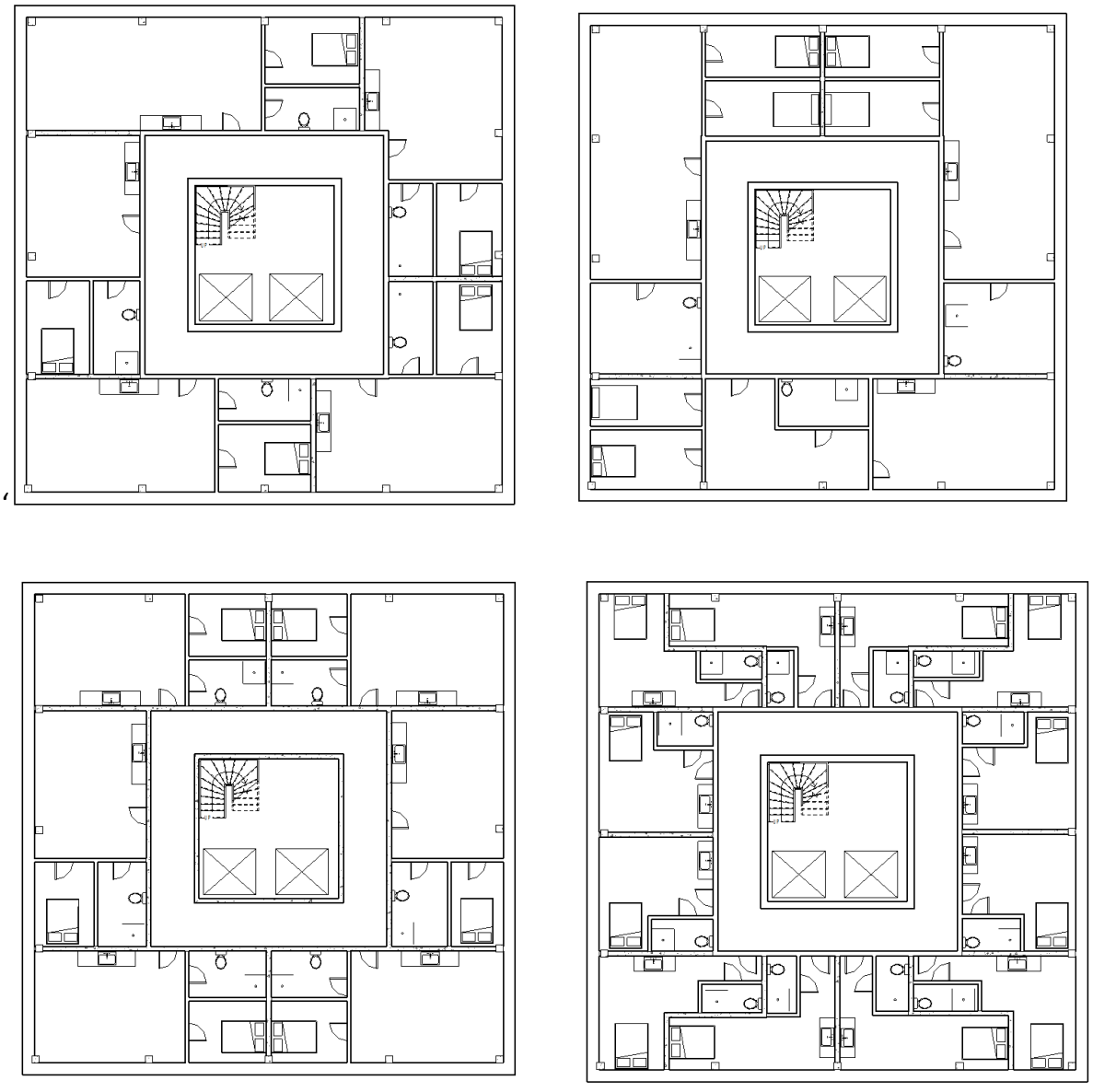

Figure A1: Space Plan Layouts

Appendix B: Material Impact Option 1 + 2

CLASS	MATERIAL	QUANTITY	QTY_TYPE	THICKNESS_MM	VOLUME_M3
Columns	Reinforced Concrete	7,43	M3	400 x 400	7,43
Core Walls	Reinforced Concrete	69,6	M2	250	17,4
Load-Bearing Walls	Reinforced Concrete	116	M2	200	23,2
SLAB	Reinforced Concrete	365	M2	250	91,25

Figure B1: Material Quantities Option 1 + 2

53 Tonnes CO_2e 2 657 € Social cost of carbon

Carbon Heroes Benchmark

Results

Life-Cycle Assessment for Level(s) in compliancy with EN 15978 Download Results Summary

	Result category	Global warming kg CO2e	Biogenic carbon storage kg CO2e bio	Ozone Depletion kg CFC11e	Acidification kg SO2e	Eutrophication kg PO4e	Formation of ozone of lower atmosphere kg Ethenee	Abiotic depletion potential (ADP-elements) for non fossil resources kg Sbe	Abiotic depletion potential (ADP-fossil fuels) for fossil resources MJ	
A1-A3	Construction Materials	5,09E+04	0,00E+00	2,26E-04	6,06E+01	1,34E+01	2,44E+00	3,83E-02	2,74E+05	Details
A4	Transportation to site	8,96E+02		1,73E-04	3,73E+00	8,09E-01	6,24E-02	5,57E+00	2,36E+04	Details
A5	Construction/installation process	1,59E+02		9,48E-06	4,59E-01	1,50E-01	3,94E-02	5,55E-02	1,53E+03	Details
B1	Use phase									Hide empty
B3	Repair	0,00E+00		0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	Details
B4-B5	Material replacement and refurbishment									Hide empty
B6	Energy consumption									Hide empty
B7	Water use									Hide empty
C1-C4	End of life	1,19E+03		2,24E-04	5,51E+00	1,15E+00	9,37E-02	7,79E+00	3,26E+04	Details
D	External impacts (not included in totals)	-1,50E+04		-7,95E-04	-6,08E+01	-9,10E+00	-8,67E+00	-6,85E-02	-2,00E+05	Details
	Total	**5,31E+04**	**0,00E+00**	**6,32E-04**	**7,03E+01**	**1,55E+01**	**2,64E+00**	**1,35E+01**	**3,31E+05**	

Figure B2: Environmental Footprint Option 1 + 2

Appendix C: Material Impact Option 3

CLASS	MATERIAL	QUANTITY	QTY_TYPE	THICKNESS_MM	VOLUME_M3
Columns	Reinforced Concrete	6,78	M3	400 x 400	6,78
Core Walls	Reinforced Concrete	74,4	M2	250	18,6
Load-Bearing Walls	Reinforced Concrete	106	M2	200	21,2
SLAB	Reinforced Concrete	365	M2	200	73
Screed	Foam Concrete	365	M2	250	91,25

Figure C1: Material Quantities Option 3

62 Tonnes CO_2e 3 118 € Social cost of carbon

Carbon Heroes Benchmark

Results

Life-Cycle Assessment for Level(s) in compliancy with EN 15978 Download Results Summary

	Result category	Global warming kg CO2e	Biogenic carbon storage kg CO2e bio	Ozone Depletion kg CFC11e	Acidification kg SO2e	Eutrophication kg PO4e	Formation of ozone of lower atmosphere kg Ethenee	Abiotic depletion potential (ADP-elements) for non fossil resources kg Sbe	Abiotic depletion potential (ADP-fossil fuels) for fossil resources MJ	
A1-A3	Construction Materials	5,94E+04	0,00E+00	3,12E-04	6,32E+01	3,45E+01	4,73E+00	4,98E-02	3,21E+05	Details
A4	Transportation to site	1,03E+03		1,93E-04	3,63E+00	7,83E-01	9,18E-02	4,88E+00	2,39E+04	Details
A5	Construction/installation process	7,30E+02		1,51E-05	8,23E-01	1,05E+00	1,24E-01	8,12E-02	4,62E+03	Details
B1	Use phase									Hide empty
B3	Repair	0,00E+00		0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	Details
B4-B5	Material replacement and refurbishment									Hide empty
B6	Energy consumption									Hide empty
B7	Water use									Hide empty
C1-C4	End of life	1,15E+03		2,17E-04	5,34E+00	1,12E+00	9,07E-02	7,54E+00	3,16E+04	Details
D	External impacts (not included in totals)	-1,37E+04		-6,77E-04	-5,25E+01	-7,81E+00	-7,56E+00	-4,93E-02	-1,74E+05	Details
	Total	**6,24E+04**	**0,00E+00**	**7,37E-04**	**7,29E+01**	**3,75E+01**	**5,04E+00**	**1,26E+01**	**3,81E+05**	

Figure C2: Environmental Footprint Option 3

Appendix D: Material Impact Option 4

CLASS	MATERIAL	QUANTITY	QTY_TYPE	THICKNESS_MM	VOLUME_M3
Columns	Reinforced Concrete	6,78	M3	400 x 400	6,78
Core Walls	Reinforced Concrete	76,8	M2	250	19,2
Load-Bearing Walls	Reinforced Concrete	106	M2	200	21,2
SLAB	Reinforced Concrete	365	M2	200	73
Matrix	Plastic	5,16	kg/m2	50 x 50 x 30	1883,4 (in kg)
Topping slab	Prefab Concrete	365	M2	50	18,25

Figure D1: Material Quantities Option 4

64 Tonnes CO_2e

3 219 € Social cost of carbon

Carbon Heroes Benchmark

Results

Life-Cycle Assessment for Level(s) in compliancy with EN 15978 Download Results Summary

	Result category	Global warming kg CO2e	Biogenic carbon storage kg CO2e bio	Ozone Depletion kg CFC11e	Acidification kg SO2e	Eutrophication kg PO4e	Formation of ozone of lower atmosphere kg Ethenee	Abiotic depletion potential (ADP-elements) for non fossil resources kg Sbe	Abiotic depletion potential (ADP-fossil fuels) for fossil resources MJ	
A1-A3	Construction Materials	5,75E+04	0,00E+00	4,51E-04	8,43E+01	1,59E+01	4,24E+00	3,99E-02	4,26E+05	Details
A4	Transportation to site	9,37E+02		1,81E-04	3,92E+00	8,51E-01	6,47E-02	5,87E+00	2,48E+04	Details
A5	Construction/installation process	8,84E+02		3,57E-05	2,35E+00	3,50E-01	1,78E-01	7,67E-02	1,31E+04	Details
B1	Use phase									Hide empty
B3	Repair	0,00E+00		0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	Details
B4-B5	Material replacement and refurbishment									Hide empty
B6	Energy consumption									Hide empty
B7	Water use									Hide empty
C1-C4	End of life	5,11E+03		3,48E-04	7,81E+00	1,50E+00	2,49E-01	7,95E+00	3,95E+04	Details
D	External impacts (not included in totals)	-1,79E+04		-1,07E-03	-7,31E+01	-1,07E+01	-9,41E+00	-7,16E-02	-2,37E+05	Details
	Total	**6,44E+04**	**0,00E+00**	**1,02E-03**	**9,84E+01**	**1,86E+01**	**4,73E+00**	**1,39E+01**	**5,03E+05**	

Figure D2: Environmental Footprint Option 4

Appendix E: Material Impact Option 5

CLASS	MATERIAL	QUANTITY	QTY_TYPE	THICKNESS_MM	VOLUME_M3
Columns	Reinforced Concrete	7,94	M3	400 x 400	7,94
Core Walls	Reinforced Concrete	74,4	M2	250	18,6
Load-Bearing Walls	Reinforced Concrete	124	M2	200	24,8
SLAB	Reinforced Concrete	365	M2	200	73

Figure E1: Material Quantities Option 5

50 Tonnes CO_2e **2 479 € Social cost of carbon**

Carbon Heroes Benchmark

Results

Life-Cycle Assessment for Level(s) in compliancy with EN 15978 Download Results Summary

	Result category	Global warming kg CO2e	Biogenic carbon storage kg CO2e bio	Ozone Depletion kg CFC11e	Acidification kg SO2e	Eutrophication kg PO4e	Formation of ozone of lower atmosphere kg Ethenee	Abiotic depletion potential (ADP-elements) for non fossil resources kg Sbe	Abiotic depletion potential (ADP-fossil fuels) for fossil resources MJ	
A1-A3	Construction Materials	4,75E+04	0,00E+00	2,49E-04	5,75E+01	1,30E+01	2,95E+00	4,17E-02	2,62E+05	Details
A4	Transportation to site	8,37E+02		1,61E-04	3,42E+00	7,42E-01	6,02E-02	5,06E+00	2,17E+04	Details
A5	Construction/installation process	1,74E+02		1,04E-05	5,03E-01	1,65E-01	4,31E-02	6,08E-02	1,68E+03	Details
B1	Use phase									Hide empty
B3	Repair	0,00E+00		0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	Details
B4-B5	Material replacement and refurbishment									Hide empty
B6	Energy consumption									Hide empty
B7	Water use									Hide empty
C1-C4	End of life	1,10E+03		2,07E-04	5,09E+00	1,07E+00	8,64E-02	7,20E+00	3,01E+04	Details
D	External impacts (not included in totals)	-1,37E+04		-7,19E-04	-5,51E+01	-8,24E+00	-7,86E+00	-6,11E-02	-1,82E+05	Details
	Total	**4,96E+04**	**0,00E+00**	**6,28E-04**	**6,66E+01**	**1,50E+01**	**3,14E+00**	**1,24E+01**	**3,16E+05**	

Figure E2: Environmental Footprint Option 5

Appendix F: Worst Case LCA

	1A	1B	2	3	4	5
0	51940	51940	51940	61199	59282	48487
12,5	0	6315,75	0	1836	0	0
25	0	6315,75	0	1836	0	0
37,5	0	6315,75	0	1836	0	0
50	1192	1192	1192	1836	0	0
62,5	x	x	x	1836	0	0
75	x	x	x	1155	0	0
87,5	x	x	x	x	0	0
100	x	x	x	x	10390	0
112,5	x	x	x	x	0	0
125	x	x	x	x	0	0
137,5	x	x	x	x	0	0
150	x	x	x	x	0	0
162,5	x	x	x	x	0	0
175	x	x	x	x	0	0
187,5	x	x	x	x	0	0
200	x	x	x	x	5105	1101
	53132	72079,25	53132	71534	74777	49588

Figure F1: Worst Case LCA

Appendix G: Mid case LCA

	1	2	3	4	5	
0	51940	51940	61199	59282	48487	
12,5	6315,75	0	1836	0	0	
25	6315,75	0	1836	0	0	
37,5	6315,75	0	1836	0	0	
50	6315,75	0	1836	0	0	
62,5	6315,75	0	1836	0	0	
75	1192	1192	1836	0	0	
87,5	x	x	1836	0	0	
100	x	x	1155	10390	0	
112,5	x	x	x	0	0	
125	x	x	x	0	0	
137,5	x	x	x	0	0	
150	x	x	x	0	0	
162,5	x	x	x	0	0	
175	x	x	x	0	0	
187,5	x	x	x	0	0	
200	x	x	x	10390	0	
212,5	x	x	x	0	0	
225	x	x	x	0	0	
237,5	x	x	x	0	0	
250	x	x	x	5105	1101	
	84710,75	53132	75206	85167	49588	

Figure G1: Mid Case LCA

Appendix H: Best Case LCA

	1A	1B	2	3	4	5
0	51940	51940	51940	61199	59282	48487
12,5	0	6315,75	0	1836	0	0
25	0	6315,75	0	1836	0	0
37,5	0	6315,75	0	1836	0	0
50	0	6315,75	0	1836	0	0
62,5	0	6315,75	0	1836	0	0
75	0	6315,75	0	1836	0	0
87,5	0	6315,75	0	1836	0	0
100	1192	1192	1192	1836	10390	0
112,5	x	x	x	1836	0	0
125	x	x	x	1836	0	0
137,5	x	x	x	1836	0	0
150	x	x	x	1836	0	0
162,5	x	x	x	1836	0	0
175	x	x	x	1836	0	0
187,5	x	x	x	1836	0	0
200	x	x	x	1155	10390	0
212,5	x	x	x	x	0	0
225	x	x	x	x	0	0
237,5	x	x	x	x	0	0
250	x	x	x	x	0	0
262,5	x	x	x	x	0	0
275	x	x	x	x	0	0
287,5	x	x	x	x	0	0
300	x	x	x	x	5105	1101
	53132	97342,25	53132	89894	85167	49588

Figure H1: Best Case LCA

Appendix I: Module A + B LCC

Option	Construction costs	Extra costs	Total Costs
1	812.000	0	812.000
2	812.000	53750	865.750
3	868.000	36500	904.500
4	896.000	27375	923.375
5	868.000	0	868.000

Figure I1: Costs Module A

	1	**2**	**3**	**4**	**5**
0	812000	865750	904500	923375	868000
12,5	1542000	1011750	1415500	1288375	1160000
25	2272000	1157750	1926500	1653375	1452000
37,5	3002000	1303750	2437500	2018375	1744000
50	3732000	1449750	2948500	2383375	2036000

Figure I2: Costs Module B

Appendix J: Worst Case LCC

	1	2	3	4	5
0	812000	865750	904500	923375	868000
12,5	994500	902250	1032250	1014625	941000
25	1177000	938750	1160000	1105875	1014000
37,5	1359500	975250	1287750	1197125	1087000
50	2171500	1841000	1415500	1288375	1160000
67,5	2354000	1877500	1543250	1379625	1233000
75	2536500	1914000	2447750	1470875	1306000
87,5	2719000	1950500	2575500	1562125	1379000
100	3531000	2816250	2703250	1653375	1452000
112,5	3713500	2852750	2831000	1744625	1525000
125	3896000	2889250	2958750	1835875	1598000
137,5	4078500	2925750	3086500	1927125	1671000
150	4890500	3793300	3991000	2018375	1744000
167,5	5073000	3829800	4118750	2109625	1817000
175	5255500	3866300	4246500	2200875	1890000
187,5	5438000	3902800	4374250	2292125	1963000
200	5620500	4768550	4502000	3215500	2831000
212,5	5803000	4805050	4629750	3306750	2904000
225	5985500	4841550	5534250	3398000	2977000
237,5	6168000	4878050	5662000	3489250	3050000
250	6980000	5743800	5789750	3580500	3123000
267,5	7162500	5780300	5917500	3671750	3196000
275	7345000	5816800	6045250	3763000	3269000
287,5	7527500	5853300	6173000	3854250	3342000
300	8339500	6719050	7077500	3945500	3415000

Figure J1: Worst Case LCC

Appendix K: Mid Case LCC

	1	2	3	4	5
0	812000	865750	904500	923375	868000
12,5	994500	902250	1032250	1014625	941000
25	1177000	938750	1160000	1105875	1014000
37,5	1359500	975250	1287750	1197125	1087000
50	1542000	1011750	1415500	1288375	1160000
67,5	1724500	1048250	1543250	1379625	1233000
75	2536500	1914000	1671000	1470875	1306000
87,5	2719000	1950500	1798750	1562125	1379000
100	2901500	1987000	2703250	1653375	1452000
112,5	3084000	2023500	2831000	1744625	1525000
125	3266500	2060000	2958750	1835875	1598000
137,5	3449000	2096500	3086500	1927125	1671000
150	4261000	2962250	3214250	2018375	1744000
167,5	4443500	2998750	3342000	2109625	1817000
175	4626000	3035250	3469750	2200875	1890000
187,5	4808500	3071750	3597500	2292125	1963000
200	4991000	3108250	4502000	2383375	2036000
212,5	5173500	3144750	4629750	2474625	2109000
225	5985500	4010500	4757500	2565875	2182000
237,5	6168000	4047000	4885250	2657125	2255000
250	6350500	4083500	5013000	3580500	3123000
267,5	6533000	4120000	5140750	3671750	3196000
275	6715500	4156500	5268500	3763000	3269000
287,5	6898000	4193000	5396250	3854250	3342000
300	7710000	5058750	6300750	3945500	3415000

Figure K1: Mid Case LCC

Appendix L: Best Case LCC

	1	2	3	4	5
0	812000	865750	904500	923375	868000
12,5	994500	902250	1032250	1014625	941000
25	1177000	938750	1160000	1105875	1014000
37,5	1359500	975250	1287750	1197125	1087000
50	1542000	1011750	1415500	1288375	1160000
67,5	1724500	1048250	1543250	1379625	1233000
75	1907000	1084750	1671000	1470875	1306000
87,5	2089500	1121250	1798750	1562125	1379000
100	2901500	1987000	1926500	1653375	1452000
112,5	3084000	2023500	2054250	1744625	1525000
125	3266500	2060000	2182000	1835875	1598000
137,5	3449000	2096500	2309750	1927125	1671000
150	3631500	2133000	2437500	2018375	1744000
167,5	3814000	2169500	2565250	2109625	1817000
175	3996500	2206000	2693000	2200875	1890000
187,5	4179000	2242500	2820750	2292125	1963000
200	4991000	3108250	3725250	2383375	2036000
212,5	5173500	3144750	3853000	2474625	2109000
225	5356000	3181250	3980750	2565875	2182000
237,5	5538500	3217750	4108500	2657125	2255000
250	5721000	3254250	4236250	2748375	2328000
267,5	5903500	3290750	4364000	2839625	2401000
275	6086000	3327250	4491750	2930875	2474000
287,5	6268500	3363750	4619500	3022125	2547000
300	6451000	3450500	4747250	4036750	3415000

Figure L1: Best Case LCC

Literature

[1] Stedebouw & Architectuur. (2010, October 4). Vraag 1: Portiek- en galerijflats slopen of vernieuwen? *Stedebouw & Architectuur*. https://www.stedebouwarchitectuur.nl/artikel/vraag-1-portiek-en-galerijflats-slopen-of-vernieuwen

[2] Van Grunsven, J. (2023, November 29). Niet meer slopen – deel 1. Rijnboutt. https://rijnboutt.nl/actueel/nieuws/niet-meer-slopen/

[3] ArchitectureCourses.org. (n.d.). Challenges and future trends in architectural design. https://www.architecturecourses.org/learn/challenges-and-future-trends-architectural-design

[4] Pelsmakers, S., & Warwick, E. (2022). Housing adaptability: new research, emerging practices and challenges. Buildings and Cities, 3(1), pp. 605–618. DOI: https://doi.org/10.5334/bc.266

[5] Moon, K. S. (2018). Dynamic interrelationship between the evolution of structural systems and façade design in tall buildings: From the Home Insurance Building in Chicago to the present. International Journal of High-Rise Buildings, 7(1), 1–16. https://doi.org/10.21022/IJHRB.2018.7.1.1

[6] Patil, S. S. (2021). Evaluation of different structural systems for high-rise construction. International Journal of Advances in Engineering and Management, 3(11), 875–885. https://doi.org/10.35629/5252-03011875885

[7] Council on Open Building. (n.d.). *What is Open Building?* Retrieved January 30, 2025, from https://councilonopenbuilding.org/what-is-open-building-1

[9] Arcadis. (2021). Circulair renoveren? Begin met de snelste cyclus: het interieur van het gebouw. Dutch Green Building Council. https://www.dgbc.nl/nieuws/circulair-renoveren-begin-met-de-snelste-cyclus-het-interieur-van-het-gebouw-6044

[10] National Circular, Economy Programme, 2023-2030, Rijksoverheid

[11] InnoDez. (n.d.). *Challenges and solutions in retrofitting MEP systems in existing structures*. https://innodez.com/challenges-and-solutions-in-retrofitting-mep-systems-in-existing-structures/

[12] New York Engineers. (n.d.). *Overcoming the challenges in retrofitting MEP systems in existing buildings*. Retrieved January 30, 5, from https://www.ny-engineers.com/blog/overcoming-the-challenges-in-retrofitting-mep-systems-in-existing-buildings

[13] GDI Engineering Design. (2023, October 12). *Designing for efficiency: Maximizing space with MEP considerations*. GDI Engineering Design. https://gdiengdesign.com/designing-for-efficiency-maximizing-space-with-mep-considerations/

[14] EDGE. (n.d.). *Fellenoord 15*. Retrieved from https://edge.tech/buildings/fellenoord-15

[15] cepezed. (n.d.). Westraven. https://www.cepezed.nl/en/project/westraven/28042/

[16] Russell, P., & Moffatt, S. (2001). *Assessing buildings for adaptability*. International Energy Agency, Energy Conservation in Buildings and Community Systems Annex 31.

[17] Schilperoort, H. (2024). *7xc1m0 Lecture 6: Elements and components*. TU/e Circularity in the Built Environment

[18] Woonbond. (2023, november). *Slopen of renoveren?*

[19] InnoDez. (n.d.). Retrofit vs. new construction: MEP design considerations. Retrieved January 30, 2025, from https://innodez.com/retrofit-vs-new-construction-projects-mep-design-considerations/

[20] OneClickLCA. (2021). Summer School: Measuring Construction Impacts

[21] Ecochain. (2023). *What is the Environmental Cost Indicator (ECI)?* Ecochain. https://ecochain.com/blog/environmental-cost-indicator-eci/

[22] Copper8, NIBE, Metabolic, & Alba Concepts. (2024, februari). Bouwen binnen planetaire grenzen: CO_2-impact van de Nederlandse bouw.

[23] MEVA USA. (n.d.). The oldest concrete structures that have lasted. https://meva.net/en-us/news/oldest-concrete-structures/

[24] Pietrzak, J. (2014). Development of high-rise buildings in Europe in the 20th and 21st centuries. Challenges of Modern Technology, 5, 31–38.

[25] Vambersky, J. N. J. A. (2004). High-rise buildings in the Netherlands: Hybrid structures and precast concrete. In L.-H. Lee, R. Klemencic, & S.-D. Kim (Eds.), Tall buildings and urban habitat: Cities in the third millennium (pp. 136–143).

[26] Scheublin, F. (2008). Tall buildings in the Netherlands: Constraints to innovation. Council on Tall Buildings and Urban Habitat.

[27] Ilgın, H.E. Space Efficiency in Tapered Super-Tall Towers. Buildings 2023, 13, 2819. https://doi.org/10.3390/buildings13112819

[28] Schoonwinkel, S., Fourie, C. J., & Conradie, P. D. F. (2016). A risk and cost management analysis for changes during the construction phase of a project. *Journal of the South African Institution of Civil Engineering, 58*(4), 11–19. https://doi.org/10.17159/2309-8775/2016/v58n4a3

[29] Shaun. (2025, January 14). *Life cycle stages*. One Click LCA Help Centre.

[30] Buyle, M., Braet, J., & Audenaert, A. (2013). *Life cycle assessment in the construction sector: A review*. *Renewable and Sustainable Energy Reviews, 26*, 379–388. https://doi.org/10.1016/j.rser.2013.05.001

[31] Morley, M. (2023, November 25). *Healthy building materials: Life cycle assessment for wellness design consultants*. Biofilico. https://biofilico.com/news/healthy-materials-building-interiors-life-cycle

[32] Buyle, M., Braet, J., & Audenaert, A. (2013). Life cycle assessment in the construction sector: A review. *Renewable and Sustainable Energy Reviews, 26*, 379–388. https://doi.org/10.1016/j.rser.2013.05.001

[33] Wikipedia contributors. (2024). *High-rise of Pécs*. In *Wikipedia, The Free Encyclopedia*. Retrieved from https://en.wikipedia.org/wiki/High-rise_of_P%C3%A9cs

[34] Roth, A. (2017). *Moscow is about to embark on Europe's biggest urban demolition project*. The Guardian. https://www.theguardian.com/cities/2017/mar/31/moscow-biggest-urban-demolition-project-khrushchevka-flats

[35] Shllaku, V. (2020, October). *Factors that contributed to the failure of the Pruitt-Igoe housing*. Conference Paper, UBT International Conference. https://doi.org/10.33107/ubt-ic.2020.28

[36] Elwyn & Palmer Consulting Engineers. (2024, August 20). The Carey Building vertical expansion. Elwyn & Palmer Consulting Engineers. https://elwynpalmer.com/the-carey-building-vertical-expansion/

[36] Onderwijsland. (2024, January 16). Almere heeft zinnen gezet op oprichten universiteit. Onderwijsland. https://www.onderwijsland.com/nieuws/6759/almere-heeft-zinnen-gezet-op-oprichten-universiteit

[37] Andersen, R., & Negendahl, K. (2023). Lifespan prediction of existing building typologies. *Journal of Building Engineering, 65*, 105696. https://doi.org/10.1016/j.jobe.2022.105696

[38] Liu, G., Xu, K., Zhang, X., & Zhang, G. (2014). Factors influencing the service lifespan of buildings: An improved hedonic model. *Habitat International, 43*, 274–282. https://doi.org/10.1016/j.habitatint.2014.04.009

[39] Baker, H., Moncaster, A., & Al-Tabbaa, A. (2017). Decision-making for the demolition or adaptation of buildings. *Proceedings of the Institution of Civil Engineers - Forensic Engineering*, 170(3), 144–156. https://doi.org/10.1680/jfoen.16.00026

[40] Clifton, J. R., & Knab, L. I. (1989). *Service life of concrete* (NUREG/CR-5466, NISTIR 89-4086). U.S. Nuclear Regulatory Commission; National Institute of Standards and Technology. https://doi.org/10.6028/NIST.IR.89-4086

[41] Pinter, G., Travnicek, L., & Arbeiter, F. (2024). *100 years lifetime of plastic pipes: Meta-study commissioned by the European Plastic Pipes and Fittings Association*. Montanuniversität Leoben

[42] Circle Economy. (n.d.). *The Netherlands: Regulating the environmental performance of buildings, taking a whole life-cycle approach*. Knowledge Hub. Retrieved from https://knowledge-hub.circle-economy.com/article/22918

[43] Zhang, C., Hu, M., Di Maio, F., Sprecher, B., Yang, X., & Tukker, A. (2022). An overview of the waste hierarchy framework for analyzing the circularity in construction and demolition waste management in Europe. *Science of The Total Environment, 803*, 149892. https://doi.org/10.1016/j.scitotenv.2021.149892

[44] bbn adviseurs. (2024, December). *Visiedocument: Marktontwikkelingen Bouwkosten*

[45] Fortus. (n.d.). *Bouwkosten per m³: Wat kost bouwen per kubieke meter?* Fortus Kennisbank. Retrieved April 25, 2025, from https://fortus.nl/kennisbank/bouwkosten/

[46] Daily Passport. (n.d.). *11 of the oldest churches in the world*. Retrieved April 25, 2025, from https://dailypassport.com/oldest-churches-in-world/

[47] Aztec Plumbing & Drains. (n.d.). *How long do plumbing pipes typically last?* Retrieved from https://www.aztecplumbing.net/blog/how-long-do-plumbing-pipes-typically-last/

[48] Chaudhary, D., Jahromi, A. B., & Keyhani, M. (2023). *Use of digital analysis methods in determination of embodied carbon of buildings in the UK*. E3S Web of Conferences, 386, 06004. https://doi.org/10.1051/e3sconf/202338606004

[49] Ministry of Foreign Affairs of the Netherlands. (2019). Making EU climate policy Paris proof. Government of the Netherlands

[50] Mlote, D. S., Budig, M., & Cheah, L**.** (2024). Adaptability of buildings: A systematic review of current research. *Frontiers in Built Environment, 10*, Article 1376759. https://doi.org/10.3389/fbuil.2024.1376759

[51] Berthold Werner. (2020). *Colosseum, Rome* [Photograph]. Wikimedia Commons. https://commons.wikimedia.org/wiki/File:Colosseo_2020.jpg

[52] Livioandronico2013. (2014, February 5). *Vatican City - Saint Peter's Basilica* [Photograph]. Wikimedia Commons. https://commons.wikimedia.org/wiki/File:Vatican_City_-_Saint_Peter%27s_Basilica.jpg

[53] Wikipedia contributors. (n.d.). *Heygate Estate*. Wikipedia. Retrieved from https://en.wikipedia.org/wiki/Heygate_Estate

[54] More, M. R., Bhumare, A. S., & Nagargoje, S. B. (2023). *The impact of different shear wall structure position on symmetric and unsymmetric tall buildings*. International Journal for Research in Applied Science and Engineering Technology (IJRASET), 11(4). https://doi.org/10.22214/ijraset.2023.50308

[55] Khadka, D., & Bhattarai, B. (2018). Seismic performance of tall buildings with braced frames. *Bulletin of Earthquake Engineering, 16*(3), 1067–1085. https://doi.org/10.1007/s10518-017-0219-2

[56] Kawade, M. P., Bangde, V. S., & Sawai, G. H. (2020). *Seismic analysis of tall building with central core as tube structure*. Rashtrasant Tukdoji Maharaj Nagpur University / VM Institute of Engineering & Technology, Nagpur, India. https://doi.org/10.35629/5252-0206300310

[57] Pure Plumbing Professionals. (n.d.). *How to repair a drain under a concrete floor*. Retrieved April 7, 2025, from https://pureplumbingpros.com.au/drainage-solutions/information/how-repair-drain-concrete-floor

[58] Adobe Stock. (n.d.). *Mechanical electrical plumbing system installed under the ceiling* [Stock photo]. https://stock.adobe.com/nl/search?k=mechanical+electrical+plumbing

[59] Green Element. (n.d.). *A short guide to product life cycle analyses: Cradle to grave*. https://www.greenelement.co.uk/blog/a-short-guide-to-product-life-cycle-analyses/cradle-to-grave/

[60] HT Raised Floor. (n.d.). *What are the differences between office raised floors?* Retrieved April 7, 2025, from https://htraisedfloor.com/differences-between-office-raised-floors/

[61] Geoplast. (n.d.). *Geoplast foundations catalogue: Lightweight infill solutions*. https://www.geoplastglobal.com/

[62] Xypedestal. (n.d.). *Adjustable pedestal for tiles*. Retrieved April 8, 2025, from http://www.xypedestal.com/adjustable-plastic-pedestal/adjustable-pedestal-for-tiles/adjustable-pedestal.html

[63] Chau, K. W., Wong, S. K., Yau, Y., & Cheung, A. K. C. (2007). *Determining optimal building height*. Urban Studies, 44(3), 597–613. https://doi.org/10.1080/00420980601131902