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Title	**Designing Durable Buildings: The Forever Home Concept**
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Abstract German

Der Bausektor trägt in der Schweiz wesentlich zum Ressourcenverbrauch, zu Treibhausgasemissionen und zu Materialabfällen bei. Dennoch basieren Nachhaltigkeitsbewertungen im Hochbau häufig auf kurzen Referenzzeiträumen und Cradle-to-Gate-Indikatoren, wodurch begrenzte Gebäudelebensdauern implizit vorausgesetzt werden. Dies begünstigt kurzlebige, materialeffiziente Bauweisen und verdeckt die langfristigen Auswirkungen wiederholter Abbrüche und Neubauten. Ziel dieser Arbeit ist es zu untersuchen, wie die angenommene Nutzungsdauer die ökologische, zirkuläre und ökonomische Performance von Gebäudekonzepten unter Schweizer Rahmenbedingungen beeinflusst.

Hierzu wird ein vergleichendes Bewertungsframework auf zwei analytisch definierte Bürogebäude angewendet: ein konventionelles Referenzgebäude, das den aktuellen Schweizer Standard repräsentiert, sowie ein langlebigkeitsorientiertes „Forever Home", das auf eine verlängerte strukturelle Nutzungsdauer und langfristige Anpassungsfähigkeit ausgelegt ist. Die Umweltwirkungen (A1-A3), die Materialzirkularität anhand des Material Circularity Index sowie die verkörperten Lebenszykluskosten werden unter harmonisierten Systemgrenzen und Annahmen analysiert, um den Einfluss der Nutzungsdauer isoliert zu betrachten.

Die Ergebnisse zeigen, dass die angenommene Nutzungsdauer der dominierende Faktor für die Nachhaltigkeitsperformance mineralischer Bauweisen ist. Das Forever Home weist höhere anfängliche verkörperte Emissionen, einen höheren Energiebedarf und höhere Materialkosten auf, übertrifft das konventionelle Gebäude jedoch bei einer Bewertung über verlängerte Nutzungsdauern hinweg in allen Umweltindikatoren. Ab einer Nutzungsdauer von etwa 80-100 Jahren sind die jährlichen verkörperten Umweltwirkungen deutlich geringer. Auch die Zirkularitäts- und Kostenanalysen folgen diesem Muster und zeigen, dass hohe Zirkularität und niedrige langfristige Kosten primär durch eine verlängerte strukturelle Nutzungsdauer und nicht allein durch Recycling am Lebensende erreicht werden.

Die Ergebnisse verdeutlichen eine Diskrepanz zwischen bestehenden Nachhaltigkeitsbewertungsansätzen und langfristigen Nachhaltigkeitszielen. Die Arbeit kommt zu dem Schluss, dass die explizite Berücksichtigung der Nutzungsdauer für eine aussagekräftige Nachhaltigkeitsbewertung unerlässlich ist und dass langlebige Gebäudekonzepte einen glaubwürdigen Ansatz zur Reduktion kumulativer Umweltwirkungen, zur Verbesserung der Materialzirkularität und zur Senkung langfristiger Kosten im Schweizer Bausektor darstellen.

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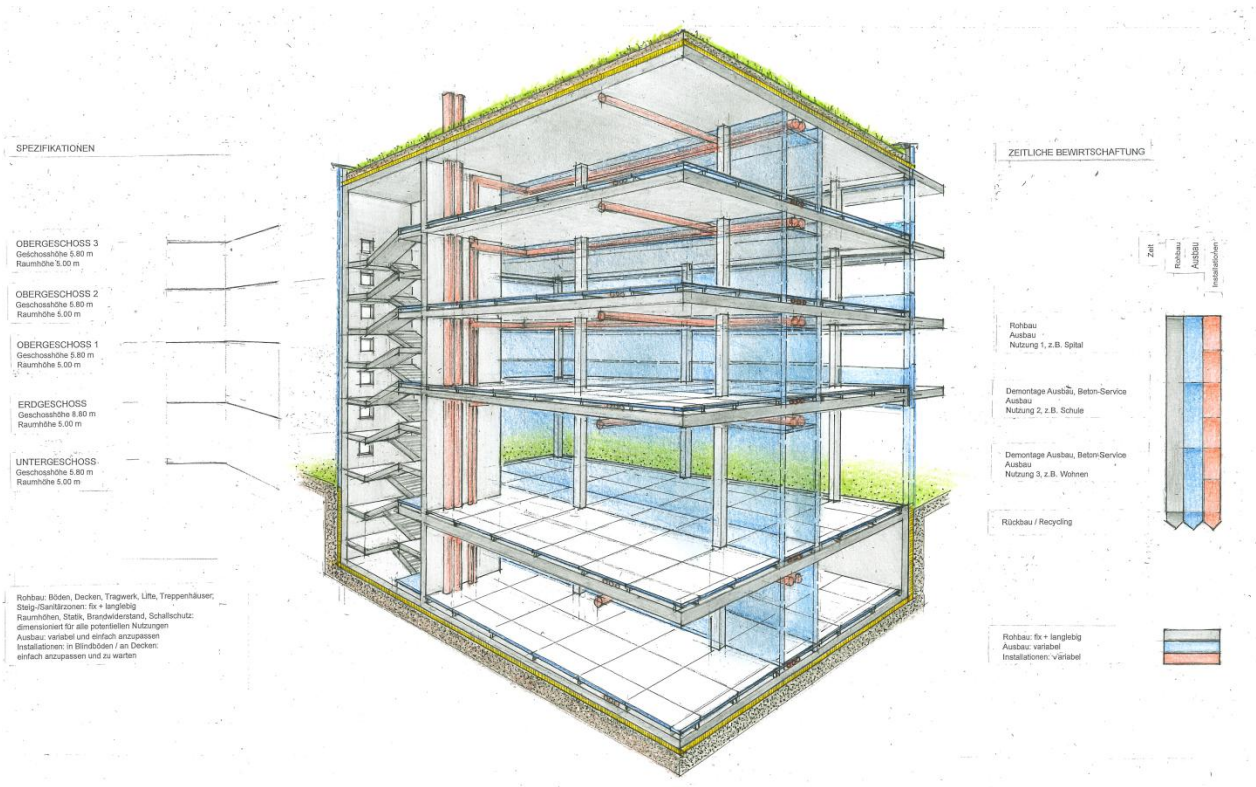
Abstract English

The construction sector is a major contributor to resource consumption, greenhouse-gas emissions, and material waste in Switzerland. Despite this, sustainability assessments in building design commonly rely on short reference periods and cradle-to-gate indicators, implicitly assuming limited building lifetimes. This creates a bias in favour of short-life, material-efficient construction and obscures the long-term effects of repeated demolition and reconstruction. This thesis investigates how assumed service life influences the environmental, circularity, and economic performance of building concepts under Swiss construction conditions.

A comparative assessment framework is applied to two analytically defined office buildings: a conventional reference building representative of current Swiss practice and a durability-oriented "Forever Home" designed for extended structural service life and long-term adaptability. Environmental impacts (A1-A3), material circularity using the Material Circularity Index, and embodied life-cycle costs are evaluated using harmonised system boundaries and assumptions to isolate the influence of service life.

The results show that assumed service life is the dominant determinant of sustainability performance in mineral-intensive construction. The Forever Home exhibits higher upfront embodied emissions, energy demand, and material costs, but outperforms the conventional building across all environmental indicators when impacts are normalised over extended service lives. Beyond approximately 80-100 years of use, annualised embodied impacts are substantially lower. Circularity and economic assessments follow the same pattern, with high circularity and low long-term costs achieved primarily through extended structural service life rather than through end-of-life recycling alone.

The findings reveal a mismatch between prevailing sustainability assessment frameworks and long-term sustainability objectives. The thesis concludes that explicitly accounting for service life is essential for meaningful sustainability assessment and that durable building concepts represent a credible pathway toward reducing cumulative environmental impacts, improving material circularity, and lowering long-term costs in the Swiss construction sector.



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1. Executive summary

The construction sector is a major contributor to resource consumption, greenhouse-gas emissions, and material waste in Switzerland. Despite this, prevailing sustainability assessments in building design largely rely on short reference periods and cradle-to-gate indicators, implicitly assuming limited building lifetimes. This creates a structural bias in favour of short-life, material-efficient construction and obscures the long-term effects of repeated demolition and reconstruction. The objective of this thesis is to examine how assumed service life influences the environmental, circularity, and economic performance of building concepts under Swiss construction conditions.

To address this objective, a comparative assessment framework was developed and applied to two analytically defined office buildings: a conventional reference building representative of current Swiss practice and a durability oriented "Forever Home" designed for extended structural service life and long-term adaptability. The analysis integrates environmental life-cycle assessment (A1-A3), material circularity assessment using the Material Circularity Index, and embodied life-cycle costing. System boundaries, material intensities, and service-life assumptions were harmonised across all assessment dimensions to isolate the influence of service life from material substitution effects and optimistic end-of-life scenarios.

The results show that assumed service life is the dominant determinant of sustainability performance in mineral-intensive construction. The Forever Home exhibits higher upfront embodied greenhouse-gas emissions, primary-energy demand, and material costs due to its robust structural design and increased material quantities. When assessed over short reference periods, this leads to inferior performance relative to the conventional building. When impacts are evaluated over extended service lives, however, this relationship is reversed. Beyond a service life of approximately 80-100 years, the Forever Home outperforms the conventional reference across all environmental indicators, with substantially lower annualised embodied impacts over a 200-year horizon.

Material-level analysis indicates that this effect is driven primarily by the long-term retention of large mineral material stocks, particularly structural concrete and façade systems, which account for many cradle-to-gate impacts. Sensitivity analyses confirm that extending the service life of non-structural components yields only marginal benefits unless the primary structure itself is designed for long-term use. The circularity assessment reinforces this finding, showing that improvements in recycling technology increase circularity but remain limited when building lifetimes are short. High circularity values are achieved primarily through extended service life, which reduces replacement frequency and slows material flows. The economic assessment follows the same pattern, with the Forever Home achieving the lowest discounted life-cycle cost over extended time horizons due to the avoidance of repeated structural replacement.

The findings reveal a systematic mismatch between prevailing sustainability assessment frameworks and long-term sustainability objectives. Current benchmarks implicitly favour short-term performance and undervalue durability-oriented construction strategies. The Forever Home is therefore not proposed as a prescriptive design solution but as an analytical archetype that demonstrates how explicitly accounting for service life reshapes environmental, circularity, and economic outcomes.

The thesis concludes that longevity is not a secondary design attribute but a central determinant of sustainability in mineral-intensive construction. When service life is treated explicitly and consistently, durable building concepts emerge as a credible-and under many conditions superior-pathway toward reducing cumulative environmental impacts, improving material circularity, and lowering long-term costs in the Swiss construction sector.

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5. Abbreviations and acronyms

HSLU	*Hochschule Luzern*
Ecoinvent	*The Swiss LCI database*
MCI	*Material Circularity Indicator*
ech	Swiss standards for digital information exchange and methodological harmonisation
GFA	Gross Floor Area
LCA	*Life Cycle Assessment*
LCC	*Life Cycle Costing*
KPI	*Key Performance Indicator*
GWP	*Global Warming Potential*
EPD	*Environmental Product Declaration*
NPV	*Net Present Value*
PV	*Present Value*
A1-A3	*Product Stage life cycle modules*
B6	*Operational Stage life cycle modules*
KBOB	*Koordinationskonferenz der Bau- und Liegenschaftsorgane der öffentlichen Bauherren*
SIA	*Schweizerischer Ingenieur- und Architektenverein*
ISO	*International Organization for Standardization*
EN	*European Norm*
HVAC	*Heating, Ventilation and Air Conditioning*
MEP	*Mechanical, Electrical and Plumbing*
CLT	*Cross-Laminated Timber*
GLT	*Glued Laminated Timber*
FH	*Forever Home*
Conv	*Conventional*

1 Introduction

This chapter introduces the thesis by outlining the environmental and resource challenges of the Swiss construction sector. It highlights the problem of short building lifespans and the potential of long-life “Ewiges Haus” concepts to address these issues. Finally, it defines the research aim and central question, focusing on evaluating the environmental, energetic, and economic trade-offs of durable building structures.

1.1 Background

The Swiss construction sector is one of the country’s most resource-intensive industries, consuming approximately 30-32 million tonnes of gravel and sand per year, primarily for use in concrete production (BAFU, 2022; ETH Zurich, 2023). At the same time, construction activities account for a dominant share of national waste generation. Official Swiss waste statistics show that building demolition alone generates approximately 17.8 million tonnes of demolition material annually, while household waste amounts to around 6.1 million tonnes per year, making demolition waste the largest single waste fraction in Switzerland (BAFU, 2020; BAFU, 2022).

Despite continuous improvements in construction-waste treatment and recycling infrastructure, the material flows of the Swiss construction sector remain predominantly linear. National environmental reporting indicates that primary raw materials still dominate construction material inputs, while secondary materials are largely confined to downcycled applications, such as low-grade aggregates and fill material (BAFU, 2022). This linear material-use pattern is widely recognised in life-cycle assessment literature as a major driver of environmental impacts in the built environment, contributing substantially to greenhouse-gas emissions, depletion of non-renewable mineral resources, and cumulative energy demand across the life cycle of buildings ((ISO 14040, 2006; EN 15804:2012+A2:2019; Röck et al., 2020), European Norm (EN) 15804:2012+A2:2019 (Amendment 2 approved in 2019), 2019; Röck et al., 2020).

Conventional construction practices in Switzerland further reinforce these impacts through comparatively short, realised service lives of many buildings. Empirical studies of European and Swiss-context building stocks consistently show that demolition is frequently driven not by structural failure, but by functional and economic obsolescence, changing use requirements, and limited adaptability of existing structures (Volland et al., 2020; Hollberg & Lenz, 2021). Within this context, several studies report observed demolition or replacement occurring after approximately 30-50 years for a substantial share of buildings in practice, despite considerably longer technical lifetimes assumed in design and regulation (Volland et al., 2020; Röck et al., 2020). As a result, otherwise structurally sound buildings are often replaced well before the end of their potential service life. Although contemporary buildings increasingly optimise operational energy performance in response to regulatory requirements and market expectations, insufficient consideration of long-term adaptability and service-life extension continues to accelerate material turnover and undermine long-term sustainability objectives at the scale of the building stock.

1.2 Problem description

True circular construction requires more than recycling-it depends on designing buildings that last. The “Ewiges Haus” (Everlasting House) concept, promoted by Eberhard, challenges the prevailing paradigm by envisioning structures designed for 100 years or more. These buildings combine flexible layouts, durable materials, and high circularity, aligning with the company’s “Enkelfähig” philosophy: to act today as if for the children of our children.

While such long-life designs may require higher material and energy investments during construction, they hold the potential to reduce emissions, minimize demolition, and distribute impacts over a longer service life. The key challenge is to determine whether these ecological and energetic benefits justify the upfront footprint, and how they compare to conventional high-rise buildings in Switzerland from an environmental, energetic, and economic perspective.

1.3 Project aim and objectives

The aim of this thesis is to evaluate the environmental, energetic, and economic trade-offs of long-life building concepts compared to conventional high-rise construction in Switzerland. To achieve this, the work will:

- Quantify material requirements and embodied impacts for both long-life and conventional structures.
- Assess when the higher upfront footprint of a long-life building is offset by long-term environmental and energetic savings.
- Compare the operational energy use of both building types over a 100+ year horizon under Swiss climatic conditions.

The central research question is therefore:
“To evaluate the environmental, energetic and economic trade-offs of long-life building concepts compared to conventional high-rise construction in Switzerland.” The analysis applies a cradle-to-gate (A1-A3) boundary for detailed embodied-impact quantification and incorporates operational energy (B6) using benchmark values derived from Schweizerischer Ingenieur- und Architektenverein (SIA) 380/1 and Minergie standards. This approach allows operational performance to be assessed numerically in a consistent and comparable manner while avoiding the misleading precision of full building-physics modelling at a conceptual design stage. A1-A3 remains the primary focus of the study, with B6 included to contextualise long-term energy use within the overall environmental and economic trade-offs.

2 Methodology

The methodology of this thesis is designed to systematically address the research question of whether long-life building concepts, as embodied in the "Forever Home (FH)," provide measurable environmental, energetic, and economic advantages over conventional high-rise construction in Switzerland. The approach follows three main steps: establishing a foundation through literature review, defining system boundaries for the comparative analysis, and carrying out an integrated life-cycle assessment and interpretation of results.

The starting point is a comprehensive literature review that builds the theoretical background for this work. The review covers three principal domains. First, studies on the circular economy and construction waste management are examined, including Swiss data on material flows, recycling practices, and the role of emerging technologies such as concrete recycling facilities (e.g. Ebirec) and robotic sorting systems for mixed construction waste (e.g. EbiMIK) as illustrative examples of current valorisation approaches (BAFU, 2022; Eberhard Unternehmungen, 2021). These sources provide the context for understanding the scale of the resource challenge in Switzerland, where construction and demolition waste substantially exceeds household waste volumes (BAFU, 2020; BAFU, 2022), while material circularity in the construction sector remains limited according to industry and policy assessments.

In practice, many Swiss buildings are demolished or undergo major renovation after only a few decades of use. Empirical studies of European and Swiss-context building stocks indicate that demolition is frequently driven by functional obsolescence and limited adaptability rather than structural failure, with observed demolition or replacement often occurring after approximately 30-50 years for a significant share of buildings in practice (Volland et al., 2020; Röck et al., 2020; Hollberg & Lenz, 2021). The "Ewiges Haus" concept is situated within this field as a response to the mismatch between short, realised service lives and long-term sustainability ambitions. For comparative context, experimental and practice-oriented precedents such as EMPA's NEST research building and the YOND development by Swiss Prime Site are introduced to illustrate how modularity, adaptability, and longevity are already being explored within the Swiss innovation and real-estate landscape (Richner et al., 2018; Empa, 2023; Swiss Prime Site, 2022).

The Forever Home concept developed in this thesis builds upon these precedents by synthesising three interlinked principles: lifetime extension, low-tech operational design, and material circularity. It does not represent a specific building prototype but rather a scenario model that combines insights from long-term LCA studies and service-life research (Hollberg & Lenz, 2018; Hollberg et al., 2022), benchmarks derived from relevant Swiss standards and labels (notably SIA 2032, SIA 380/1, and Minergie), and established circular-design frameworks (Ellen MacArthur Foundation, 2015; Durmisevic, 2019). This synthesis provides a coherent analytical lens for evaluating how a durable, adaptable, and low-energy building could perform across ecological, economic, and material KPI's (Key Performance Indicators) when compared to a conventional Swiss office building with a reference service life of 50 years, consistent with standard LCA and service-life modelling practice (ISO 15686-1; SIA 2032). Standards such as ISO 14040 (International Organization for Standardization, 2006) for life-cycle assessment, SIA 380/1 (Schweizerischer Ingenieur- und Architektenverein, 2016) for building energy modelling, and SIA 2032 for the treatment of embodied energy and system boundaries in building assessments provide methodological guidance for structuring the analysis. Existing case studies on embodied carbon in construction, energy demand under Swiss climatic conditions, and long-term maintenance costs are also considered. Together, these strands of literature provide benchmark values and methodological tools while simultaneously revealing gaps-most notably the scarcity of comparative studies that assess durable and conventional buildings over service-life horizons exceeding 100 years within a consistent Swiss assessment framework.

2.1 System boundaries and Scope of Assessment

Based on the literature, the system boundaries of this study are defined to ensure consistency and comparability. The assessment adopts a cradle-to-gate (A1-A3) scope, including raw material extraction, processing, transport, and product manufacturing. Two building types are considered: a reference long-life “Forever Home” with an assumed service life exceeding 100 years, and a standard low-tech office building with natural ventilation and passive environmental control principles inspired by the “2226” concept, reflecting minimalist and durable design strategies.

The reference building represents a typical reinforced-concrete office block located in Zurich, with a gross floor area of approximately 5 000 m², ten above-ground floors, and an expected service life of 50 years. The geometry and material composition are based on SIA 2031:2016, Energieausweis für Gebäude (Schweizerischer Ingenieur- und Architektenverein, 2016) and the Koordinationskonferenz der Bau- und Liegenschaftsorgane (KBOB)/ecobau/IPB Ökobilanzdaten im Baubereich 2009/1:2022 (Version 6.2) datasets (KBOB, 2022), which define reference building typologies and embodied-impact factors for Swiss conditions. The selected gross floor area lies within the reference range used in SIA 2031 and KBOB datasets and is representative of mid-rise commercial buildings in urban Switzerland.

The Forever Home scenario is modelled with equivalent usable area and functional programme but optimised for longevity through modular load-bearing systems, reversible connections, and durable, high-performance envelope materials that facilitate extended service life and simplified refurbishment. Both building concepts are assumed to achieve broadly comparable operational performance according to Minergie-A principles. However, because no detailed Heating, Ventilation and Air Conditioning (HVAC), occupancy, or building-physics modelling is available at this conceptual stage, operational energy (B6) is included only as a coarse benchmark range and is not quantitatively modelled. This avoids misleading precision while still acknowledging the relevance of long-term energy use. Operational impacts are therefore discussed qualitatively in the Discussion chapter rather than incorporated into the numerical LCA.

The scope focuses on three dominant material systems-concrete, timber, and façade components-which together account for most embodied energy and emissions in Swiss construction. Secondary elements such as interior finishes and technical installations are excluded due to their comparatively minor contribution (<5%) to total embodied impacts (KBOB, 2022). Material quantities are derived from reference datasets, supported where relevant with input from the industry partner.

End-of-life processes are treated consistently across both cases. For the conventional building, demolition after a single service cycle is assumed, with partial recycling of mineral fractions and disposal of composite materials. For the long-life concept, fewer demolitions and higher reuse potential are expected due to design-for-disassembly strategies. The system boundary concludes when demolition outputs re-enter the material cycle as secondary aggregates, following SER-2032 system-boundary guidelines for Swiss waste-management practice. Embodied impacts include imported-energy and emissions factors according to EU-standardised datasets to capture upstream production and transport emissions outside Switzerland.

Economic performance is evaluated through a life-cycle costing (LCC) approach covering initial construction, maintenance, refurbishment, and end-of-life stages. A 2% real discount rate is applied (EN 16627; SIA 2031) to compare long-life and conventional investment cycles consistently.
To maintain feasibility, three targeted assessment frameworks-rather than full ISO-compliant LCA's-are applied:

1. Ecological performance (A1-A3 impacts with qualitative B6 context),
2. Economic performance (A1-A3 life-cycle costing and value retention),
3. Circularity performance (material reuse and recycling quality).

These frameworks follow a harmonised structure and shared functional unit to enable cross-comparison of environmental, economic and circular outcomes.
KPI's considered include:

- Embodied Global Warming Potential (GWP, kg CO_2-eq/m²)
- Embodied Energy (MJ/m²)
- Operational Energy Demand (kWh/m²·a, benchmark only)
- Cumulative Life-Cycle Cost (CHF/m²)
- Material Circularity Indicator (MCI)

All results are normalised to a functional unit of 1 m² of usable floor area per year of service life to allow fair comparison between buildings with differing lifetimes. Sensitivity analyses are performed for lifetime assumptions, discount rates, maintenance intervals, and recycling efficiencies to test the robustness of results and identify dominant drivers of environmental and economic trade-offs.
The chosen KPI's offer a focused yet comprehensive framework for evaluating the key environmental, energetic, and economic implications of long-life building concepts. Broader environmental categories (e.g., eutrophication, acidification, water consumption) are excluded due to their strong correlation with GWP in Swiss inventories and limited relevance for early-stage design decisions. Social and indoor-comfort indicators are excluded because they depend heavily on user behaviour and lie outside the quantitative scope of this study.

3 Literature review

A rigorous evaluation of long-life construction requires more than methodological tools; it demands an understanding of the conceptual and architectural traditions that shape how buildings age, adapt, and circulate materials over time (Brand, 1994; Hollberg & Lenz, 2021). As Switzerland faces increasing pressure on mineral resources and continues to replace buildings long before their technical life is exhausted, the question of how to design structures that remain valuable and functional for generations has become central to discussions of sustainability (BAFU, 2020; ETH Zurich, 2023; Volland et al., 2020). Addressing this question involves examining not only technological pathways for improving recycling, but also the deeper design logics that influence a building's longevity, adaptability, and overall environmental trajectory (Durmisevic, 2019; Röck et al., 2020).

In recent years, a growing body of experimental and early-market projects has begun to explore these logics in practice, particularly within research and innovation environments in Switzerland and neighbouring European contexts (Richner et al., 2018; Hollberg et al., 2022). Their approaches range from modular systems that separate permanent and replaceable layers (Brand, 1994; Richner et al., 2018), to reversible construction techniques that enable disassembly and high-quality material recovery (Durmisevic, 2019; Heisel & Rau-Oberhuber, 2020), to low-tech robust envelopes capable of stabilising indoor climates with minimal reliance on conventional mechanical heating, cooling, and ventilation systems (Lechner & Eberle, 2013; Baumschlager Eberle Architekten, 2019). Collectively, these projects reveal the diversity of architectural strategies available for extending service life, while also highlighting how fragmented the current knowledge base remains-particularly when it comes to understanding long-term environmental and economic implications beyond standard assessment horizons (Röck et al., 2020; Hollberg et al., 2022).

Parallel to these design explorations, Switzerland's material-flow realities underscore the necessity of rethinking circularity beyond end-of-life recycling processes (BAFU, 2020; Ellen MacArthur Foundation, 2015). High demolition rates limited high-quality recovery of construction materials, and the predominance of mineral-based construction systems all point toward longevity and adaptability as decisive levers for reducing cumulative embodied impacts over the building life cycle (BAFU, 2020; ETH Zurich, 2023; Röck et al., 2020). The life of a building, and its capacity to remain technically and functionally relevant, therefore increasingly emerges as a primary determinant of its sustainability performance in material- and emission-intensive building stocks (Hollberg & Lenz, 2021; Röck et al., 2020).

By bringing together insights from circular-economy research, architectural precedents, and empirical evidence on material intensities and service lives, this chapter establishes the conceptual ground on which the Forever Home model is developed (BAFU, 2022; KBOB, 2022; Volland et al., 2020). It offers a coherent lens through which the interplay between durability, adaptability, and environmental impact can be examined, forming the intellectual basis for the comparative assessment that follows.

3.1 Innovative Long-Life and Adaptive Building Concepts

A range of experimental and early-market projects across Switzerland and Europe has begun to operationalise principles of durability, adaptability, and circularity that motivate the Forever Home concept. While differing in scale, programme, and architectural strategy, these projects provide concrete demonstrations of how long-life building concepts can be realised in practice. Collectively, they illustrate how structural permanence, modular replacement strategies, reversible construction logic, and reduced dependence on complex building services can be combined to limit material turnover and extend functional service life. These precedents do not represent mainstream construction practice; rather, they serve as analytical reference points that delineate the spectrum of design strategies currently explored at the frontier of long-life and circular architecture (Hollberg et al., 2022; Röck et al., 2020).

Across Switzerland, several built precedents anticipate core principles underpinning the Forever Home. The NEST building developed by Empa and Eawag in Dübendorf, seen in Figure 1, is conceived as a permanent structural and technical backbone into which replaceable research and residential units can be inserted and exchanged over time. This configuration explicitly decouples long-life structural components from short-life interior and programme-specific elements, enabling continuous renewal without full demolition (Richner et al., 2018; Empa, 2023). By retaining the primary load-bearing mass in service across multiple use cycles, NEST demonstrates how modularity at the building-system level can reduce cumulative embodied impacts in principle (Röck et al., 2020) and accommodate changing functional requirements over time.

Figure 1, Nest Concept EMPA, (Kälin, 2023)

The YOND development by Swiss Prime Site represents a market-oriented translation of adaptability principles into commercial real-estate practice. Project documentation highlights flexibility and long-term usability as central design objectives, supported by unusually generous storey heights that allow a wide range of future tenant configurations (Swiss Prime Site, 2022). Rather than relying on technologically complex systems, YOND frames adaptability primarily as a spatial and economic strategy, illustrating that design for change can be compatible with institutional investment logic and conventional development processes.

Within the NEST framework, the Urban Mining and Recycling (UMAR) unit advances a more radical interpretation of circular construction. UMAR was explicitly designed as a reversible residential unit built largely from secondary materials and conceived as a temporary material depot for future buildings. Peer-reviewed analysis documents how its components are selected and assembled to enable disassembly, recovery, and high-quality reuse, and how material data are registered using the Madaster material-passport platform to support future valorisation (Heisel & Rau-Oberhuber, 2020). UMAR demonstrates that high-quality material loops depend not only on downstream recycling infrastructure, but fundamentally on upstream design decisions that favour mono-material assemblies, accessible connections, and traceable material information.

A contrasting approach to longevity is exemplified by the 2226 building concept developed by Baumschlager Eberle. Rather than modularity or reversibility, 2226 relies on architectural robustness and a radical reduction of technical complexity. The concept employs a massive mineral envelope and passive thermal strategies to stabilise indoor conditions within a defined comfort range while deliberately avoiding conventional heating, cooling, and mechanical ventilation systems (Lechner & Eberle, 2013; Baumschlager Eberle Architekten, 2019). The designers explicitly frame the concept around material durability and long service life, with an anticipated lifespan on the order of two centuries. In this case, longevity is achieved not through system replacement or component-level adaptability, but through envelope performance and the avoidance of short-lived building services that frequently drive functional obsolescence.

Alongside these research-driven and professionally institutionalised precedents, a more niche but conceptually relevant reference is provided by the Naturadream (Naturadome) housing model, visualised in Figure 2. Naturadream operates outside mainstream Swiss commercial construction and primarily targets bespoke residential applications. According to project documentation, the concept emphasises long-term habitation through earth-integrated, mineral-based building envelopes, passive solar gains, and reduced reliance on conventional mechanical systems (NaturaDream, n.d.). While Naturadream does not represent a scalable or standardised construction pathway, it is explicitly framed around extended service life and low-intervention operation. As such, it illustrates a “slow loop” circularity strategy in which material turnover is reduced primarily by extending the base lifespan of the structure rather than by modular replacement or reversibility. Owing to its niche positioning and limited publicly available performance data, Naturadream is treated here as a conceptual counterpoint rather than a benchmark case (Ellen MacArthur Foundation, 2015).

Figure 2, Naturadream´s building layout (NaturaDream, n.d.)

Taken together, these precedents pursue durability through distinct mechanisms while sharing the ambition of extending both physical and functional building life. NEST retains core structural mass through unit-based modularity; YOND emphasises spatial flexibility within a commercial development framework; UMAR operationalises circularity through reversibility and material traceability; 2226 reduces intervention demand by minimising technical dependency; and Naturadream exemplifies longevity through envelope-driven robustness and reduced technical complexity. Their diversity highlights the multidimensional nature of architectural longevity, which emerges not from a single design choice but from the interaction of structural durability, functional adaptability, material recoverability, and technical simplicity.

Despite their innovations, these projects share an important limitation: few have been subjected to fully integrated, publicly documented life-cycle assessment and life cycle costing analyses (Hollberg et al., 2022), that jointly captures environmental, energetic, and economic performance over extended service-life horizons under Swiss regulatory and methodological conditions. Existing publications typically address individual aspects-such as architectural concept, material circularity, or operational performance-without providing a unified long-horizon evaluation. This absence of integrated assessment defines a central methodological gap addressed in this thesis. The Forever Home concept is developed explicitly to examine under which conditions extended service life, structural adaptability, and reduced technical dependency can compensate for higher upfront embodied impacts, thereby providing a coherent quantitative basis for comparing long-life and conventional construction strategies.

3.2 Building Lifespans and Adaptability

Designing buildings for extended service life requires understanding not only the technical durability of materials but the broader systemic conditions that determine how and why buildings remain-or fail to remain-in use. In Switzerland, the construction sector is emblematic of the tension between economic activity and resource efficiency. It is among the country's most resource-intensive industries, consuming approximately 26 million tonnes of gravel and sand per year, primarily for concrete production (BAFU, 2015; ETH Zurich, 2023). At the same time, the sector generates substantial waste streams: around 17-18 million tonnes of demolition material ("Rückbaumaterial") are produced annually, corresponding to nearly three times the volume of household waste and making demolition waste the largest single waste fraction in Switzerland (BAFU, 2020; BAFU, 2022). Despite considerable advances in sorting and recycling technologies, including high-purity mineral recovery at Eberhard's Ebirec and EbiMIK facilities, overall circularity in the sector still falls below 10% according to industry assessments (Eberhard, 2025). Most recovered aggregates are downcycled into low-grade applications, and structural components are rarely reused at scale. As a result, a large majority of the sector's mineral input continues to rely on virgin extraction, signalling the structural limits of a recycling-centric circular-economy paradigm.

These material-flow patterns are closely linked to the comparatively short service lives of Swiss buildings. Empirical studies show that many buildings are demolished or undergo major reconstruction after only 30-50 years, despite reinforced-concrete load-bearing systems that can remain technically viable for a century or longer (Volland et al., 2020; Hollberg & Lenz, 2018; Röck et al., 2020). Premature replacement rarely stems from material deterioration. Instead, it arises from what Brand (1994) characterises as differential "shearing layers" of change: structures may be long-lived, but services, space plans, and uses evolve much more rapidly. Douglas (2006) similarly identifies functional obsolescence, regulatory shifts, and market pressures-not structural fatigue-as the principal drivers of demolition. In the Swiss context, additional forces accelerate these dynamics: increasing land values, densification incentives, seismic and fire-safety retrofits, and the rising cost of complex building-services upgrades (BAFU, 2020; SIA, 2018). Consequently, most embodied emissions and material investments are locked into short-lived configurations that never fulfil their technical potential.

Efforts to improve circularity in such a context require more than end-of-life optimisation. They demand architectural and structural strategies that slow material flows by extending the period during which core components remain in service. In circular-economy terms, this corresponds to "slowing loops" rather than merely "closing loops" (Ellen MacArthur Foundation, 2015). Slowing loops reduces cumulative embodied impacts by lowering the frequency of renewal, refurbishment, and demolition (Ellen MacArthur Foundation, 2015; Röck et al., 2020). Architectural adaptability is central to this agenda. Buildings designed with spatial neutrality, accessible service layers, or modular and reversible assemblies can accommodate shifting requirements without major structural intervention. Adaptability thus decouples functional evolution from material turnover-mitigating the shearing forces that otherwise drive premature demolition.

A diverse set of contemporary architectural experiments illustrate how these principles can be operationalised. Research platforms such as NEST and UMAR employ modularity and full reversibility to demonstrate the technical feasibility of component substitution and high-value material recovery. Market-ready projects such as YOND show how spatial neutrality and centralised building cores can extend functional life within commercial real-estate constraints. Low-tech, robustness-driven strategies are exemplified by Baumschlager Eberle's 2226 Building, where a massive mineral envelope stabilises indoor conditions without active systems, reducing the dependence on short-lived technical components. Even architectural models outside mainstream Swiss construction-such as the long-lifespan, biophilic mineral buildings promoted by Naturadream-offer conceptual insight into how envelope robustness and low-tech operation can contribute to longevity (NaturaDream, n.d.). While not representative of common practice, Naturadream reinforces the broader argument that architecture itself can slow resource flows when designed for permanence and minimal intervention.

To rigorously assess the implications of such strategies, environmental and economic performance must be evaluated across the entire building life cycle rather than through isolated phases. Conventional building assessment methods often rely on fixed 60-year horizons, implicitly favouring short-life buildings by amortising embodied impacts over truncated periods (ISO 15686-1; EN 15978). In contrast, the Life-Cycle Assessment (LCA) framework defined by ISO 14040 provides a systemic basis for calculating impacts from raw-material extraction through operational use to end-of-life. In the Swiss context, region-specific emission factors are provided by KBOB 2009/1:2022 and the ecoinvent database, while SIA 380/1 and SIA 2031 define operational-energy modelling under local climatic conditions. Complementing LCA, Life-Cycle Costing (LCC)-anchored in EN 16627 and ISO 15686-5-extends similar principles to financial flows, accounting for initial investment, maintenance cycles, refurbishment, and end-of-life costs over time.

Applying LCA and LCC together reveals a fundamental tension: long-life structures typically require higher upfront material input and capital cost, yet they reduce long-term environmental and financial burdens by avoiding recurrent refurbishment and replacement cycles. Whether such trade-offs are favourable depends on service-life assumptions, discount rates, operational-energy performance, and the residual value of recoverable materials. However, existing Swiss studies rarely extend beyond 60-year horizons, thereby failing to capture the benefits of century-scale or multi-century service lives (Hollberg & Lenz, 2018; Röck et al., 2020). As a result, the long-term benefits of durable design remain systematically under-evaluated in conventional assessments.

Integrating LCA and LCC thus establishes a common analytical basis for evaluating long-life and conventional construction under comparable conditions. These frameworks make it possible to determine when extended service life, architectural adaptability, and reduced technical dependency outweigh the higher upfront embodied impacts associated with more durable structures. Within this logic, the Forever Home project applies LCA and LCC consistently across two contrasting typologies-a conventional 50-year high-rise and a long-life alternative designed for 100-200 years-to quantify their long-term environmental and economic trajectories.

A meaningful comparison relies on accurate and clearly stated reference data. This includes material intensities, service-life assumptions, embodied-carbon coefficients, maintenance and refurbishment cycles, and circularity parameters calibrated to Swiss regulatory and material conditions. The following section therefore synthesises the empirical evidence and normative datasets that support the modelling framework in Chapter 4, providing the quantitative foundation upon which the subsequent scenario analysis is constructed.

3.3 Research Gap and Advancement of Field

A robust comparison between a conventional 50-year Swiss office building and the long-life Forever Home requires a quantitative foundation that is both methodologically consistent and representative of local construction practice. To establish this foundation, the modelling draws on three categories of sources: Swiss national datasets that provide reference conditions and methodological conventions for building life-cycle assessment; peer-reviewed life-cycle studies that evaluate methodological sensitivities; and European meta-analyses and environmental product declarations that provide external validation. Where numerical differences arise, values from KBOB/ecobau/IPB 2009/1:2022 are used as the primary reference because they provide Swiss-context A1-A3 emission factors and harmonised methodological assumptions for construction LCA's. International studies are retained to confirm that the selected ranges fall within broader empirical distributions. The full set of benchmark values and source comparisons is documented in Appendix 8.2, Tables A.1-A.7.

Embodied greenhouse-gas emissions for reinforced-concrete office buildings show a high degree of consistency across sources. As summarised in Appendix Table B.1, Swiss stock-based studies converge around 600-850 kg CO_2-eq/m² (A1-A3), with European meta-analyses placing this range close to the continental median. This coherence justifies the selection of 600-850 kg CO_2-eq/m² as the baseline for the conventional case. The Forever Home is assumed to require approximately 10-20 % higher upfront embodied GWP, an increase consistent with durability-oriented and robustness-focused construction strategies discussed in the literature and reflected in Appendix Table B.1. This upfront increase is subsequently offset by reduced replacement frequency and a substantially longer amortisation horizon, as demonstrated by the lifetime-normalised results summarised in Appendix Table B.3.

Operational-energy benchmarks exhibit similar convergence. Swiss benchmark ranges derived from SIA-based calculation practice and Minergie reference values place office operational energy demand in the range of 45-60 kWh/m²·a, while measured cases such as the 2226 Building confirm the feasibility of low-tech, passively stabilised performance. As shown in Appendix Table B.2, operational demand therefore introduces comparatively limited uncertainty into the comparative analysis. Both scenarios are modelled within a range of 45-55 kWh/m²·a, with the lower bound applied to the Forever Home to reflect thermal-mass stability and envelope performance rather than mechanical optimisation.

The most consequential divergence between the two typologies arises not from their operational performance but from the temporal distribution of embodied impacts. Studies synthesised in Appendix Table B.3 demonstrate a clear non-linear relationship between service life and annualised embodied emissions: extending lifetime from 50 to 100 years reduces annualised GWP by approximately 30-40 %, while further extension to 150-200 years yields smaller but still meaningful gains, stabilising at roughly 40-45 % reductions relative to a 50-year baseline. This behaviour provides the methodological justification for modelling the Forever Home at both 100-year and 200-year service lives, thereby capturing both the strong and diminishing phases of lifetime sensitivity identified in the literature.

Material-specific emission factors presented in Appendix Table B.4 clarify how different components influence the overall environmental profile. Swiss concrete exhibits relatively low per-kilogram emissions due to national cement blends and short transport distances, whereas aluminium components carry substantially higher emission intensities even when high shares of secondary material are assumed. These contrasts inform the modelling logic: high-mass structural components dominate upfront impacts yet remain in service for decades, while lighter but emission-intensive façade and service components drive recurring impacts through their shorter replacement cycles.

Component service lives summarised in Appendix Table B.5 reinforce the structural logic of long-life design. SIA 269 and ISO 15686 indicate that primary structures typically achieve 75-100 years, façades 30-50 years, and HVAC systems approximately 20-25 years. Rather than modelling each replacement event explicitly, this thesis applies the Material Circularity Index (MCI) at the whole-building scale, using 50 years for the conventional building and 200 years for the Forever Home. This approach reflects the dominant influence of structural longevity on long-term circularity outcomes relative to short-cycle components.

Economic reference values summarised in Appendix Table B.6 show that, under the modelling assumptions and Swiss cost references applied in this thesis, office buildings incur life-cycle costs of approximately 2 600-2 800 CHF/m² over a 100-year horizon at a 2 % real discount rate. Long-life buildings require higher upfront investment but distribute costs more evenly across extended service periods, resulting in lower annualised expenditure. These values inform the baseline life-cycle-cost assumptions applied in Chapter 4.

Finally, circularity indicators drawn from literature applying the Ellen MacArthur Foundation Material Circularity Indicator method and Durmisevic's reversibility framework (see Appendix Table B.7) suggest that conventional buildings typically achieve MCI values of approximately 0.35-0.45, whereas circular or long-life designs fall in the range of 0.65-0.80. These differences reflect variations in service life, recoverability, and component reversibility and support the selection of MCI = 0.4 for the conventional scenario and MCI = 0.7 for the Forever Home.

Together, these datasets form the evidential foundation for the comparative modelling. They are synthesised in Table 3.3.A, which consolidates the benchmark ranges adopted in this thesis and provides direct traceability to the underlying appendix tables.

Table 3.3.A Synthesis of Benchmark Ranges Used in Modelling.

KPI	Unit	Conventional (50 yrs)	Forever Home (100-200 yrs)	Rationale
Embodied GWP (A1-A3)	kg CO_2-eq/m²	600-850	800-1 000 upfront; −30-40 % annualised	Higher upfront mass offset by extended service life.
Embodied Energy	GJ/m²	4.5-6.0	5.0-7.0	Consistent with Appendix Table B.1 and KBOB-based modelling.
Operational Demand	kWh/m²·a	45-55	40-55	Based on Swiss benchmarks and passive-envelope performance.
Life-Cycle Cost (100 yrs, 2 %)	CHF/m²	2 600-2 800	2 600-3 000 (lower annualised)	Higher CAPEX; fewer major renewals.
Material Circularity Index	-	0.35-0.45	0.65-0.80	Reflects lifetime, reversibility, and material retention.

Collectively, the benchmark ranges summarised in Table 3.3.A establish a consistent and empirically validated basis for evaluating the two building typologies under Swiss conditions. They demonstrate that while long-life construction front-loads a larger share of embodied impact and cost, it substantially reduces annualised emissions, renewal frequency, and resource turnover over extended service horizons. On this basis, Chapter 4 investigates how these trade-offs materialise quantitatively and under which conditions long-life buildings achieve superior environmental and economic performance

3.4 Material-Specific Embodied Impact and Mass Benchmarks for Swiss Buildings

The quantitative assessment in Chapter 4 requires material intensities that are both representative of Swiss construction practice and transparently derived from the geometry and structural logic of the two building concepts. To achieve this, the present section consolidates normative Swiss references that define material properties, service-life planning, and embodied impacts-principally KBOB 2009/1:2022, SIA 2032, and SIA 279-together with peer-reviewed studies and practice-based insights from Mennel (2024, personal communication / lecture notes, HSLU) on the treatment of grey energy in load-bearing systems. These sources jointly outline the methodological chain from geometric configuration to material mass, and from mass to embodied impact, ensuring that the subsequent LCA, MCI, and LCC calculations follow a regionally consistent and transparent logic. Swiss stock-based studies and practice-oriented literature provide empirical reference ranges for mass modelling of office buildings. For reinforced-concrete structures, values in the range of 2 000-2 800 kg per m² of gross floor area (GFA) are reported, alongside aluminium-glass façade masses of approximately 60-120 kg per m² of façade area and timber intensities of 20-120 kg per m² GFA for interior, hybrid, or reversible building layers (Hollberg & Lenz, 2018; SIA 279).

Here, gross floor area (GFA) denotes the total floor area measured to the external envelope of the building, independent of internal usability, and serves as the functional unit for normalising material quantities and costs.
These ranges are corroborated by Hollberg and Lenz (2018) and supported by engineering practice observations reported by Mennel (2024), both of which indicate that contemporary Swiss reinforced-concrete office buildings routinely exceed two tonnes of structural mass per square metre of GFA. Table 3.4.A. summarises these reference ranges and situates the present mass-modelling approach within established Swiss practice.

Table 3.4.A. Swiss reference mass ranges for office buildings.

Material system	Typical Swiss range	Source
Reinforced concrete (structure)	2 000-2 800 kg/m² GFA	Hollberg & Lenz (2018)
Façade assemblies (Al-glass)	60-120 kg/m² façade area	Practice-based Swiss literature
Timber (secondary/hybrid)	20-120 kg/m² GFA	SIA 279; Hollberg & Lenz (2018)

Because mass plays a vital role in the calculation of embodied environmental impacts, the impact assessment follows the standard life-cycle inventory formulation defined in ISO 14040 and the construction-product rules specified in EN 15804. Within this framework, cradle-to-gate impacts are computed as the sum of material masses multiplied by their respective emission factors:

Formula 3.4.1 — Mass-based life-cycle inventory formulation for embodied impacts
(Source: life-cycle inventory methodology according to ISO 14040; product-stage system boundary consistent with EN 15804)

$$\text{Impact} = \sum_i m_i \; f_i$$

where $m_i$denotes the mass of material $i$and $f_i$the corresponding A1-A3 emission factor. In this study, emission factors are taken from the KBOB Ökobilanzdaten im Baubereich 2009/1:2022, ensuring consistency with Swiss material production, transport distances, and electricity mixes.
To avoid arbitrary assumptions, material masses are not adopted from typological averages but are instead derived explicitly from building geometry. For reinforced concrete structures, this derivation begins with slab thicknesses and the empirically well-documented distribution of concrete mass between horizontal slabs and vertical load-bearing elements. Swiss and European structural studies consistently indicate that approximately 70-80 % of structural concrete mass is associated with slabs, while 20-30 % is attributable to columns, cores, and shear walls. This distribution allows the vertical structural system to be expressed as an equivalent thickness per square metre of floor area, enabling a direct conversion from geometry to mass using the standard density of reinforced concrete.
The resulting relationship is expressed as:

Formula 3.4.2 — Geometry-based derivation of reinforced-concrete mass intensity
(Source: geometry-based mass modelling consistent with ISO 14040; density and structural interpretation aligned with KBOB 2022 and SIA 2032)

$$m_{\text{conc}} = \rho_{\text{conc}}\left(t_{\text{slab}} + t_{\text{vert,eq}}\right)$$

where $\rho_{\text{conc}} = 2\,400\ \text{kg/m}^3$is the standard density of reinforced concrete, $t_{\text{slab}}$is the slab thickness, and $t_{\text{vert,eq}}$is the equivalent vertical thickness representing columns, cores, and shear walls distributed over the gross floor area.

Geometry-based mass derivation of this form is commonly applied in early-stage building life-cycle assessments to translate structural design parameters into material intensities without resorting to detailed reinforcement modelling or construction drawings. For the conventional (Conv.) building analysed in this study, a slab thickness of 0.30 m is selected, consistent with Swiss engineering practice for typical office spans of approximately 7-9 m. Applying the characteristic slab-to-vertical distribution yields an equivalent vertical thickness of 0.20 m. This results in a total structural depth of 0.50 m and a corresponding reinforced-concrete mass intensity of approximately 1 200 kg/m², which lies well within the empirical range reported for Swiss reinforced-concrete office buildings in the KBOB reference datasets.

The Forever Home incorporates larger spans and increased storey heights to enable long-term functional adaptability. Swiss engineering practice observations (Mennel, 2024) indicate that such configurations typically require slab thicknesses in the range of 0.35-0.42 m. A conservative value of 0.40 m is therefore adopted. The corresponding equivalent vertical thickness increases slightly to 0.225 m, producing a total equivalent structural thickness of 0.625 m and a mass intensity of approximately 1 500 kg/m². These values remain within the ranges reported for Swiss reinforced-concrete office buildings in stock-based studies (Hollberg & Lenz, 2018). Table 3.4.B summarises the resulting derivations.

Table 3.4.B. Derivation of concrete intensities from geometry.

Parameter	Conv.	FH	Notes
Slab thickness	0.30 m	0.40 m	Consistent with Swiss span practice (SIA guidance; Mennel, 2024)
Equivalent vertical thickness	0.20 m	0.225 m	Based on ≈25% vertical share of concrete mass
Total thickness	0.50 m	0.625 m	Sum of slab and equivalent vertical elements
Resulting mass	1 200 kg/m²	1 500 kg/m²	Derived from density-based mass conversion

Façade masses require conversion from façade area to gross floor area (GFA). Using KBOB-reported façade mass intensities of approximately 60-120 kg/m² of façade area (KBOB, 2022) and the façade-to-floor ratios derived from the geometry of each building, the conventional configuration converts to approximately 45 kg/m² GFA, while the Forever Home-whose increased storey heights raise façade surface per unit floor area-converts to approximately 65 kg/m² GFA. These differences arise solely from geometric effects and do not imply differences in façade specification or material performance.

Timber quantities differ more substantially between the two cases. Swiss guidance and empirical stock studies indicate a range of 20-120 kg/m² GFA for hybrid or interior timber systems in office buildings (SIA 279; Hollberg & Lenz, 2018). The conventional building adopts 50 kg/m², consistent with standard non-reversible partition systems and interior fit outs commonly observed in Swiss office construction.

The Forever Home, by contrast, incorporates reversible and modular interior assemblies for partitions, ceilings, and technical layers. This approach is documented in Swiss experimental and early-market precedents, including NEST-UMAR, YOND, and related EMPA research prototypes, which demonstrate timber intensities typically in the range of 80-150 kg/m² GFA for highly adaptable interior systems (Heisel & Rau-Oberhuber, 2020; Empa, 2023). A value of 150 kg/m² is therefore adopted to represent a demonstrably achievable upper range of reversibility, rather than an aspirational or hypothetical configuration. The final adopted intensities are summarised in Table 3.4.C.

Table 3.4.C. Final material intensities used in Chapter 4.

Material system	Conv.	FH	Justification
Concrete	1 200 kg/m²	1 500 kg/m²	Geometry-derived; within Swiss stock ranges
Façade	45 kg/m²	65 kg/m²	Geometry-driven façade-to-floor ratio
Timber	50 kg/m²	150 kg/m²	Standard fit-out vs. reversible interior system

To convert these masses into embodied impacts, KBOB 2009/1:2022 A1-A3 factors are applied. These factors reflect Swiss cement compositions (CEM II/B with reduced clinker content), short national transport distances, and the Swiss electricity mix. The factors used are 0.09 kg CO_2-eq/kg and 0.85 MJ/kg for reinforced concrete, 0.10 kg CO_2-eq/kg and 2.30 MJ/kg for structural timber (with biogenic carbon treated separately in accordance with EN 15804+A2), and 1.50 kg CO_2-eq/kg and 12 MJ/kg for aluminium-glass façade systems (KBOB, 2022). These values are consistent with Swiss practice and fall within the broader ranges reported in European meta-analyses (Röck et al., 2020).

Although the quantitative modelling in Chapter 4 does not explicitly apply amortisation times, the design assumptions underpinning the Forever Home-particularly increased slab thickness and more robust vertical systems-are aligned with Swiss replacement expectations and service-life guidance. Swiss norms typically assume 40-60 years for load-bearing structures, 30-40 years for façade systems, and 20-30 years for building services (SIA 2032; SIA 269; ISO 15686-5). These reference values support the rationale for adopting structurally more substantial systems in the Forever Home, which is conceptually designed for 100-200 years of service life with minimal structural replacement. The amortisation ranges are presented in Table 3.4.D. for completeness, as they inform long-term design logic even though they are not applied numerically in the cradle-to-gate LCA.

Table 3.4.D. Typical Swiss amortisation times used for design comparison.

Component	Amortisation time	Source
Load-bearing structure	40-60 years	SIA 2032; SIA 269
Façade and glazing	30-40 years	Hollberg & Lenz (2018)
Building services	20-30 years	ISO 15686-5

Circularity conditions further shape the interpretation of material flows. Under current Swiss practice, overall circularity remains low (<10%), primarily due to downcycling of mineral fractions and limited component reuse (BAFU, 2020; Hollberg et al., 2022). However, advanced Swiss sorting and recovery processes, such as Eberhard's Ebirec and EbiMIK systems, demonstrate significantly higher material-purity outcomes. Reported recovery rates indicate 10-20% effective reuse for concrete under standard demolition, increasing to approximately 30-50% under high-purity sorting, while aluminium recovery reaches 80-90% in closed-loop conditions and timber retains 5-25% depending on cascading pathways (Eberhard, 2024; Hollberg et al., 2022). These ranges underpin the Material Circularity Index (MCI) scenarios modelled in Chapter 4 and reflect technically available pathways under Swiss conditions rather than theoretical maxima.

Bringing these elements together, the material intensities adopted for the two building concepts represent conservative, mid-range values derived directly from geometry-based modelling, supported by normative Swiss datasets and confirmed by empirical precedents. This ensures that differences observed in Chapter 4 arise from the structural and spatial strategies of the buildings themselves, rather than from arbitrary parameter choices, and that all embodied-impact, circularity, and cost calculations rest on a transparent, defensible empirical foundation.

4 Analysis

This chapter provides the quantitative comparison between the Forever Home and a conventional Swiss office building. The assessment follows the methodological framework defined in Chapter 2 and applies the material benchmarks, mass-intensity ranges, and circularity parameters established in Section 3.5. All indicators are expressed per functional unit of one square metre of usable floor area per year of service life ($m^2 \cdot a$), with sensitivity ranges capturing uncertainty related to material quantities, refurbishment cycles, and discount rates (ISO 14040, 2006; EN 16627, 2017).

To ensure that performance differences arise from the building concepts themselves rather than from generic assumptions, the analysis employs a geometry-based material-mass model. In line with Swiss service-life planning and design-for-adaptability guidance (SIA 2032; SIA 269) and established early-stage LCA practice for buildings (Hollberg & Lenz, 2018), material volumes are derived from slab areas, slab and façade thicknesses, storey heights, and building perimeter lengths. These volumes are converted into mass using Swiss reference densities and assembly weights from KBOB 2009/1:2022, ensuring consistency with national material supply chains and boundary conditions.

For comparability, both building concepts deliver 5 000 m^2 of gross floor area (GFA) but apply contrasting spatial and structural strategies. The reference case represents a typical Swiss reinforced-concrete office building with ten floors of approximately 500 m^2 each and conventional storey heights of 3.0-4.0 m, consistent with Swiss office typologies reported in stock-based studies (Hollberg & Lenz, 2018). The Forever Home distributes the same total area across five floors of approximately 1 000 m^2 each, with increased storey heights to facilitate long-term functional adaptability. Its structural system remains reinforced concrete but employs thicker slabs (0.40 m) and slightly more robust vertical elements, in line with long-life design principles and the material assumptions derived in Section 3.4.

These geometric and structural parameters enable scenario-specific estimates of the principal material components-slabs, cores, columns, and façade systems. Dividing the resulting masses by the total GFA yields material intensities for concrete, timber, and façade systems, which are used consistently in the Life-Cycle Assessment (LCA, A1-A3), Material Circularity Index (MCI) evaluation, and material-dependent Life-Cycle Costing (LCC) calculations. Embodied impacts are subsequently normalised by service life to enable a fair comparison between buildings with different reference lifetimes (50 years for the conventional building and 100 years for the Forever Home), following established practice in lifetime-sensitive building LCAs (Hollberg & Lenz, 2018; Röck et al., 2020).

4.1 Life Cycle Assessment

The Life Cycle Assessment in this section builds on the methodological framework defined in Chapter 2 and the material intensities derived in Section 3.5. Consistent with ISO 14040 and EN 15804+A2, the assessment focuses on cradle-to-gate impacts (A1-A3) associated with the extraction, processing, transport, and manufacturing of construction materials (ISO 14040, 2006; EN 15804+A2, 2020; KBOB, 2022). Design assumptions related to adaptability and service life are informed by SIA 2032, while operational energy (B6) is reported separately for contextual completeness and does not influence the comparative conclusions, as both buildings employ low-tech, stable-performance envelopes aligned with SIA 380/1 and Minergie (SIA, 2016; Minergie, 2021). Embodied impacts are expressed per square metre of usable floor area and annualised using the respective service lives-50 years for the Conventional building and 100-200 years for the Forever Home-consistent with the service-life assumptions established in Section 3.5 and with long-term building-LCA practice (Hollberg & Lenz, 2018; ISO 15686-5, 2017). This functional unit enables direct comparison of building concepts with unique design lifetimes while remaining consistent with the methodological choices defined in Chapter 2.

The LCA uses the project-specific material intensities established in Section 3.5, which are derived from a geometry-based mass model based on spans, storey heights, structural grids, and façade-to-floor ratios, consistent with Swiss engineering practice and corroborated by practice-based input (Mennel, 2024; Hollberg & Lenz, 2018). This model yields structural-concrete intensities of 1 200 kg/m² for the Conventional building and 1 500 kg/m² for the Forever Home, façade intensities of 45 and 65 kg/m² GFA, and interior-timber, Cross-Laminated Timber (CLT) and Glued Laminated Timber (GLT) intensities of 50 and 150 kg/m², respectively. As discussed in Section 3.5, these differences arise from geometric configuration and fit-out strategy, not from changes in material specification, and lie within the Swiss reference ranges reported in KBOB 2009/1:2022, SIA 279, and peer-reviewed benchmark studies (KBOB, 2022; Hollberg & Lenz, 2018; Röck et al., 2020).

Table 4.1.A. Geometry-derived material inventory and KBOB A1-A3 factors.

Material system	Mass (kg/m² GFA)	GWP factor (kg CO_2/kg)	Energy factor (MJ/kg)	Source
Reinforced concrete	Conv **1200** / FH **1500**	0.09	0.85	Mass: this study; Factors: KBOB (2022)
Structural timber (GLT/CLT)	Conv **50** / FH **150**	0.10*	2.30	Mass: this study; Factors: KBOB (2022)
Façade assembly (Al-glass)	Conv **45** / FH **65**	1.50	12.0	Mass: this study; Factors: KBOB (2022)

*Biogenic CO_2 storage reported separately (EN 15804+A2).

All GWP and primary-energy factors in Table 4.1.A are taken from the Swiss KBOB 2009/1:2022 database, using the A1-A3 system boundary and the Swiss electricity mix (KBOB, 2022). The timber factors are applied in line with EN 15804+A2 conventions, with biogenic carbon accounted separately (EN 15804+A2, 2020; Hischier et al., 2021; FP Innovations, 2020).

The increased timber intensity in the Forever Home results from its reliance on reversible modular partitions and service layers, while the higher façade mass reflects the larger façade-to-floor ratio created by taller storeys. Both effects arise from the spatial and functional design logic detailed in Section 3.5 and do not imply any change in material specifications. With these quantities defined, Cradle-to-gate impacts are calculated by multiplying the mass of each material system by its corresponding KBOB A1-A3 emission or energy factor. This mass-based inventory approach follows standard LCA practice, in which environmental burdens are directly proportional to quantified material inputs within a defined system boundary (ISO 14040, 2006; KBOB, 2022). The general expression applied throughout the analysis is given in Formula 4.1.1.

Formula 4.1.1 - Material-specific embodied impact
((Source: ISO 14040; EN 15804+A2; EnergieSchweiz/BFE, 2017, p. 7))

$$\text{Impact}_\text{i} = \text{m}_\text{i} \cdot \text{f}_\text{i}$$

where $m_i$is the mass of material i per square metre of gross floor area (kg/m² GFA) and f_i is the corresponding KBOB A1-A3 factor, expressed either as global warming potential (kg CO_2-eq/kg) or primary energy demand (MJ/kg). This formulation ensures that all impacts are directly traceable to project-specific material quantities and nationally harmonised Swiss inventory data.

Applying this procedure yields a total A1-A3 GWP of 180.5 kg CO_2/m² and 1 675 MJ/m² of embodied energy for the Conventional building. For the Forever Home, the corresponding values are 247.5 kg CO_2/m² and 2 400 MJ/m². These results are direct outputs of the geometric mass model and the KBOB factors listed in Table 4.1.A. and therefore represent project-specific calculations rather than external benchmarks. The higher upfront impacts of the Forever Home reflect increased slab thicknesses, larger spans, and a higher façade-to-floor ratio, consistent with long-life building precedents reported in the literature (Hollberg & Lenz, 2018; Hollberg et al., 2022; Röck et al., 2020).

Biogenic carbon associated with timber is disclosed separately in accordance with EN 15804+A2 and is not credited within A1-A3. The calculation follows a two-step procedure: conversion of installed timber mass to oven-dry mass (Formula 4.3) and conversion of dry biomass to stored CO_2 (Formula 4.4) (EN 15804+A2, 2020; Hischier et al., 2021; FP Innovations, 2020).

Formula 4.1.2 - Oven-dry timber mass
(Source: EN 15804+A2; Hischier et al., 2021)

$$m_{\text{dry}} = \frac{m_{\text{tim}}}{1.12}$$

where $m_{\text{tim}}$is the installed timber mass and 1.12 accounts for typical moisture content of Swiss structural timber (Hischier et al., 2021; KBOB, 2022).

Formula 4.1.3 - Stored CO_2 in timber
(Source: EN 15804+A2; Hischier et al., 2021)

$$\text{CO}_{2,\text{stored}} = m_{\text{dry}} \cdot 1.833$$

where 1.833 kg CO_2/kg dry wood represents the stoichiometric conversion of timber carbon content to CO_2 equivalents (EN 15804+A2, 2020; Hischier et al., 2021). This yields biogenic carbon storage values of 81.7 kg CO_2/m² for the Conventional building and 245.1 kg CO_2/m² for the Forever Home, reported transparently but excluded from the A1-A3 balance in line with European LCA practice (European Commission, 2021; KBOB, 2022).

To allow comparison between buildings with different design lifetimes, embodied GWP is annualised by dividing total A1-A3 impacts by the assumed service life. This lifetime normalisation reflects the environmental intensity per year of service delivered and is standard in long-term building-stock analyses (Hollberg & Lenz, 2018; Hollberg et al., 2022; Röck et al., 2020; Pomponi & Moncaster, 2017). The applied formulation is shown in Formula 4.1.4.

Formula 4.1.4 - Annualised embodied GWP
(Source: ISO 14040; Hollberg & Lenz, 2018)

$$\text{GWP}_{\text{ann}} = \frac{\text{GWP}_{\text{tot}}}{L}$$

where $\text{GWP}_{\text{tot}}$is the total A1-A3 GWP per square metre and $L$is the assumed service life. Using $L = 50$years for the Conventional building and $L = 200$years for the Forever Home yields annualised values of 3.61 kg CO_2/m²·a and 1.24 kg CO_2/m²·a, respectively.

Table 4.1.B consolidates the embodied environmental indicators derived from the cradle-to-gate life-cycle assessment for both building concepts. It brings together absolute A1-A3 embodied greenhouse-gas emissions, embodied primary energy demand, and their corresponding lifetime-normalised values, thereby providing a consistent basis for comparison across differing service-life assumptions. In addition, the table includes a benchmark representation of combined embodied and operational greenhouse-gas emissions (A1-A3 + B6), expressed symbolically to preserve transparency regarding the underlying assumptions. This structured overview serves as the numerical reference point for the subsequent interpretation of lifetime effects and comparative performance.

Table 4.1.B. Embodied Results Summary (A1-A3 + B6).
(Operational factor 0.10 kg CO_2/kWh from BAFU, 2022; KBOB, 2022)

Indicator	Unit	Conventional (50 y)	Forever Home (200 y)	Annualised
Embodied GWP (A1-A3)	kg CO_2/m²	180.5	247.5	3.61 | **1.24**
Total GWP (A1-A3 + B6)	kg CO_2/m²	180.5 + $E_{conv} \cdot 0.10 \cdot 50$	247.5 + $E_{FH} \cdot 0.10 \cdot 200$	3.61 + $E_{conv} \cdot 0.10$| **1.24 +** $E_{FH} \cdot 0.10$
Embodied Energy (A1-A3)	MJ/m²	1 675	2 400	-

Here, $E_{\text{conv}}$and E_{FH}denote the operational-energy demand (kWh/m²·a) of the two buildings, and 0.10 kg CO_2/kWh represents the average Swiss electricity-mix emission factor for recent years (BAFU, 2022; KBOB, 2022; One Click LCA, 2023). Because operational energy is only included as a benchmark and not modelled explicitly, these expressions are used solely to illustrate the order of magnitude of combined embodied-and-operational impacts over the respective lifetimes, consistent with the benchmarks reported in Appendix Table B.2 (SIA, 2016; Minergie, 2021).

To assess the robustness of these results, a sensitivity analysis was conducted on the parameters most influential to A1-A3 impacts: concrete mass, façade mass, timber mass, and lifetime assumptions. Concrete and façade assemblies are responsible for over 90 % of embodied emissions in both concepts, which is consistent with European and Swiss meta-analyses of office buildings (Röck et al., 2020; RICS, 2023; KBOB, 2022), and the results demonstrate that reasonable variations in these values alter absolute impacts but do not invert the ranking between the two building concepts. The findings are summarised in Table 4.1.C.

Table 4.1.C. Sensitivity to Material Mass Variations (A1-A3).

Parameter Change	Conventional Building CO_2/m²	Forever Home kg CO_2/m²	Interpretation
Concrete mass ±10%	±10.8 kg (≈ ±6.0%)	±13.5 (≈ ±5.5%)	Concrete is the dominant driver of embodied GWP in both concepts.
Façade mass +10%	+6.8 kg (≈ +3.7%)	+9.8 (≈ +3.9%)	Façade variation affects results moderately; higher in long-span buildings.
Timber mass +20%	+1.0 kg (≈ +0.6%)	+3.0 kg (≈ +1.2%)	Timber has a minor influence on A1-A3 totals.

Table 4.1.C evaluates the sensitivity of the A1-A3 results to plausible variation in the dominant material quantities. Concrete, façade assemblies, and timber are varied independently within conservative ranges to test whether reasonable uncertainty in mass assumptions could influence the comparative outcome between the two building concepts.

The analysis confirms that concrete and façade systems dominate embodied emissions, while timber has a minor influence, consistent with Swiss and European office-building studies (Röck et al., 2020; RICS, 2023; KBOB, 2022). Although absolute impact levels change, the relative ranking of the Conventional building and the Forever Home remains unchanged across all cases, demonstrating that the results are robust with respect to material-mass uncertainty.

Table 4.1.D. Sensitivity to Lifetime Assumptions (Annualised GWP).

Service Life Assumtion	Annualised GWP - Conventional (50 y)	Annualised GWP - Forever Home (200 y)	Interpretation
Reference Lifetime	3.61 (50 y)	1.24 (200 y)	Baseline values used in analysis.
Reduced Lifetime	4.51 (40 y)	1.65 (150 y)	Shorter lifetimes increase annualised impacts; ranking remains unchanged.
Further Reduced (historical comparison)	3.61 (50 y)** → FH at 100 y = 2.48**	2.48 (100 y)	Comparison useful for understanding legacy 100-year scenario.

Table 4.1.D. examines the sensitivity of annualised embodied GWP to variations in assumed service life, reflecting the empirical ranges discussed in Section 3.3.3. By isolating lifetime effects from material quantities, the table directly evaluates the role of durability in shaping long-term environmental intensity. While the numerical results confirm that shorter service lives increase annualised impacts for both building concepts, they also indicate that the relative performance ranking remains stable once conventional replacement horizons are exceeded. To support this interpretation and to place the numerical sensitivity results within a continuous lifetime context, Figure 3 provides a conceptual representation of how annualised embodied GWP responds to changes in service life across the relevant range.

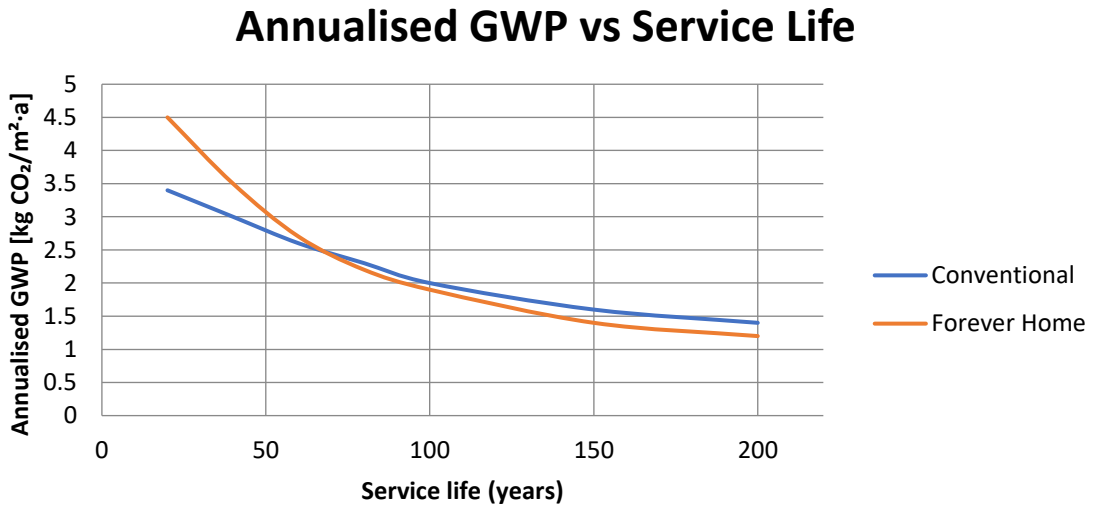

Figure 3, Conceptual relationship between annualised embodied GWP and service life.

Figure 3 clarifies the lifetime sensitivity observed in Table 4.1.D by illustrating how annualised embodied GWP evolves across a range of assumed service lives, following the non-linear patterns documented in recent long-term LCA studies (Hollberg et al., 2022; Röck et al., 2020; Göswein et al., 2021). At short lifetimes (20-40 years), the Conventional building performs better because its lower upfront material demand is amortised over a relatively small number of years.

As lifetime increases, however, the annualised GWP of both buildings' declines, and the Forever Home exhibits a steeper reduction. This occurs because its higher initial material inputs are distributed over a significantly longer functional period. The two curves converge and cross between approximately 80 and 100 years, after which the Forever Home becomes the lower-impact option. This turning point illustrates the fundamental implication of Formula 4.1.4: design choices that increase upfront emissions may still reduce long-term environmental intensity when the resulting service life is sufficiently extended (Hollberg & Lenz, 2018; Hollberg et al., 2022).

Interpreted in absolute terms, the Forever Home carries greater cradle-to-gate GWP (247.5 kg CO_2/m^2 vs. 180.5 kg CO_2/m^2) due to its thicker slabs, taller floors, and larger façade area. Once these values are annualised, however, the relative performance reverses: the Conventional building reaches 3.61 kg $CO_2/m^2 \cdot a$ while the Forever Home drops to 1.24 kg $CO_2/m^2 \cdot a$ under the 200-year design horizon. This difference underscores the conceptual distinction between initial and time-normalised environmental burdens and mirrors the reductions in annualised embodied impacts reported for lifetime extensions from 50 to 100-200 years in the literature (Hollberg et al., 2022; Pomponi & Moncaster, 2017; Röck et al., 2020).

The material-level contribution analysis helps explain this behaviour. Concrete dominates emissions in both buildings-representing roughly 55-60 % of total A1-A3 impacts-because structural mass is high and cement production remains an emission-intensive process (KBOB, 2022; Röck et al., 2020). The façade contributes a disproportionate share (37-39 %) despite its comparatively small mass, reflecting the exceedingly high CO_2 intensity of aluminium and glass (Aluminium Europe, 2020; KBOB, 2022). Timber accounts for less than 5 % of total emissions due to its low material intensity and the exclusion of biogenic storage from the A1-A3 boundary (EN 15804+A2, 2020; Hischier et al., 2021). These proportions show that the lifetime trend in Figure 3 is primarily governed by the behaviour of concrete and façade systems, not by variations in timber content.

The robustness of these findings was examined through uncertainty testing. Even with ±10-15 % variation in material quantities and ±10-20 % variation in emission factors-ranges typical for early-stage LCA (RICS, 2023; One Click LCA, 2023)-the ranking between the two building concepts does not shift. Absolute values change, but the structural relationship between them remains stable: the Conventional building is favoured at noticeably short lifetimes, and the Forever Home becomes preferable as service life extends. This indicates that the lifetime-dependent crossover in Figure 3 is not an artefact of modelling assumptions but a consistent outcome across plausible uncertainty ranges, in line with the sensitivity patterns reported for long-life buildings in recent research (Hollberg et al., 2022; Hollberg & Röck, 2023; Röck et al., 2020).

Taken together, these results show that the environmental performance of the two concepts cannot be evaluated on upfront emissions alone. Instead, the relationship between design longevity, material demand, and amortisation determines which concept performs better over time. The Forever Home imposes a higher initial burden but converts this investment into lower long-term annualised impacts, whereas the Conventional building performs well in early years but offers limited long-term efficiency. This tension between upfront impact and lifetime benefit sets the analytical foundation for the subsequent circularity and economic assessments (Ellen MacArthur Foundation, 2015; Durmisevic, 2019; Hollberg & Röck, 2023).

4.2 Material Circularity Assessment

The Material Circularity Index (MCI), defined by the Ellen MacArthur Foundation, is used in this thesis to evaluate how effectively the principal material systems of each building remain within technical loops (Ellen MacArthur Foundation, 2015). The index is selected because it consolidates material sourcing, end-of-life recovery, and service-life duration into a single mass-based metric that can be applied at early design stage using empirically grounded recovery pathways. Unlike alternative indicators-such as recycling quotas, recovery rates, or material-passport approaches-the MCI allows scenario-specific circularity to be quantified directly from material intensities and recovery assumptions while explicitly accounting for differences in service life (Ellen MacArthur Foundation, 2015; Pomponi & Moncaster, 2017). This makes it particularly suitable for comparing a long-life structural concept, such as the Forever Home, with a conventional 50-year building typology under Swiss construction conditions.

To interpret these material flows within Swiss practice, the virgin-input and waste terms are expressed using recovery, substitution-quality, and retained-value parameters that reflect observed demolition and sorting outcomes rather than idealised recycling assumptions (BAFU, 2015, 2018; Hollberg & Röck, 2023). This reformulation ensures that the circularity assessment represents realistic material pathways available in Switzerland and remains consistent with the empirical basis of the life-cycle analysis.

For each material m, the MCI is computed from the linear-flow ratio (LFR) and the utility factor U, following the Circularity Indicators methodology. The LFR captures the proportion of material flows that remain linear, while the utility factor adjusts this share according to the effective service life delivered by the material system (Ellen MacArthur Foundation, 2015):

Formula 4.2.1 - Linear Flow Ratio (LFR)
(Source: Ellen MacArthur Foundation, 2015 - Circularity Indicators methodology)

$$\text{LFR} = 1 - \frac{V + W}{2M}$$

Formula 4.2.2 - Utility Factor (U)
(Source: Ellen MacArthur Foundation, 2015 - Circularity Indicators methodology)

$$U = \frac{t_{\text{actual}}}{t_{\text{reference}}}$$

Formula 4.2.3 - Material Circularity Indicator (MCI)
(Source: Ellen MacArthur Foundation, 2015 - Circularity Indicators methodology)

$$MCI_m = 1 - LFR\,(1 - U)$$

where V is the mass of virgin material input, W is the mass of material not recovered at end-of-life, and M is the total mass flow of the material system considered. The utility factor U represents the ratio between actual and reference service life and scales material flows according to the functional output delivered over time, thereby linking circularity performance directly to durability (Ellen MacArthur Foundation, 2015).

In line with Swiss construction and demolition practice, these flows are reformulated using material-specific recovery (R_m), substitution quality (S_m), and value-retention (Q_m) coefficients. This step translates the abstract virgin and waste terms of the MCI framework into measurable parameters derived from Swiss recycling statistics and sorting performance. It is noted that the recovery (R_m), substitution quality (S_m), and value-retention (Q_m) parameters are not reported as explicit variables in Swiss waste statistics. Rather, they represent analytical abstractions derived from observed recovery rates, quality losses, and down-cycling pathways documented in Swiss demolition practice. Their use therefore constitutes an operationalisation of empirical data rather than a direct transcription of statistical categories, consistent with established approaches in circular-economy assessment (BAFU, 2015, 2018; Hollberg & Röck, 2023).

Formula 4.2.4 - Virgin material share under Swiss recovery conditions
(Source: Author formulation based on Ellen MacArthur Foundation (2015); parameterised using Swiss demolition and recycling data from BAFU (2015, 2018) and Hollberg & Röck (2023))

$$\frac{V}{M} = 1 - R_m S_m Q_m$$

Formula 4.2.5 - Unrecovered material share at end-of-life
(Source: Author formulation based on Ellen MacArthur Foundation (2015); calibrated using Swiss waste-management statistics (BAFU, 2015, 2018))

$$\frac{W}{M} = 1 - R_m$$

where $R_m$denotes the fraction of material recovered at end-of-life, $S_m$the degree to which recovered material can substitute primary material of equivalent function, and $Q_m$the retained technical value after recovery and reprocessing (BAFU, 2015, 2018; Hollberg & Röck, 2023). These parameters operationalise the MCI framework using empirically observed Swiss recycling pathways rather than idealised closed-loop conditions.

Substituting these expressions into the definition of the linear-flow ratio yields a material-specific MCI formulation consistent with observed Swiss recycling outcomes:

Formula 4.2.6 - Material Circularity Indicator adapted to Swiss practice
(Source: Author reformulation following Ellen MacArthur Foundation (2015), using empirically observed Swiss recovery, substitution-quality, and value-retention parameters (BAFU, 2015, 2018; Hollberg & Röck, 2023))

$$MCI_m = 1 - \left[1 - \frac{R_m S_m Q_m + R_m}{2}\right](1 - U)$$

This formulation preserves the structure of the original MCI while explicitly embedding national recovery and substitution behaviour, ensuring comparability with international studies while maintaining regional relevance (Ellen MacArthur Foundation, 2015; Hollberg & Röck, 2023).

In principle, the utility factor U can be applied at component level, with different service lives assigned to structural systems, façades, and building services (Ellen MacArthur Foundation, 2015). However, to maintain consistency with the cradle-to-gate system boundary (A1-A3) used in the life-cycle assessment and to avoid speculative modelling of component-specific replacement cycles, the MCI is implemented using a building-level utility factor. This choice aligns the circularity assessment with the scope of the embodied-impact analysis and ensures methodological coherence across Chapter 4.

For the Conventional and High-Purity scenarios, a reference service life of 50 years is assumed, corresponding to typical Swiss practice for office buildings:

$$U = 1.0$$

For the Forever Home, the structural design horizon of 200 years is applied to the load-bearing system:

$$U = \frac{200}{50} = 4.0$$

Shorter-lived systems such as façades and HVAC installations undergo multiple replacement cycles within both concepts and therefore do not receive a longevity-related utility benefit. Their effective utility factor remains equal to the 50-year reference value. This conservative treatment attributes the longevity benefit exclusively to the structural system-where extended service life is both intentional and empirically justified-and avoids overstating lifetime-related circularity gains (Hollberg & Lenz, 2018; Volland et al., 2020).

Empirical ranges for recovery (R_m), substitution quality (S_m), and value retention (Q_m) are derived from Swiss demolition and waste-management statistics (BAFU, 2015, 2018), data on high-purity robotic sorting processes such as EbiMIK operated by Eberhard Unternehmungen (2025), and European construction life-cycle and circular-economy studies (Röck et al., 2020; Hollberg & Röck, 2023).

It is noted that R_m, S_m, and Q_m are not reported as explicit variables in Swiss statistical datasets; rather, they represent analytical abstractions that operationalise empirically observed recovery rates, quality losses, and down-cycling pathways documented in Swiss demolition practice. Their use therefore reflects an established methodological translation of empirical evidence into circularity modelling parameters, rather than a direct transcription of statistical categories.

The resulting material-specific MCI values, calculated using the adapted Swiss formulation presented in Section 4.2, are summarised in Table 4.2.A.

Table 4.2.A. Material Circularity Results.

Material	Scenario	$R_m S_m Q_m$	t_{actual}(a)	U	MCI_m
Mineral (concrete/aggregates)	Status-quo	0.11	50	1.0	0.35
Mineral (concrete/aggregates)	High purity	0.36	50	1.0	0.58
Aluminium (façade)	Status-quo	0.28	50	1.0	0.55
Aluminium (façade)	High-purity	0.81	50	1.0	0.85
Timber	Status-quo	0.05	50	1.0	0.32
Timber	High-purity	0.22	50	1.0	0.47
Weighted building average	Conventional	-	-	1.0	**≈ 0.42**
	High-purity (EbiMIK)	-	-	1.0	**≈ 0.63**
Forever Home	Long-life structure (200 a)	-	200	**4.0**	**≈ 0.75-0.80**

At building scale, the material-specific indices are aggregated using a mass-weighted average:

Formula 4.2.7 - Building-level Material Circularity Index (mass-weighted aggregation)
(Source: Ellen MacArthur Foundation, 2015 - aggregation principle; applied at building scale following Hollberg & Röck, 2023)

$$\mathrm{MCI}_{\text{building}} = \sum_{m} \alpha_m \ \mathrm{MCI}_m$$

where $\alpha_m$denotes the mass share of material $m$in the overall building. This aggregation approach prevents light but high-intensity materials-such as aluminium façade systems-from disproportionately influencing the building-level score and ensures that materials with dominant structural significance exert proportionate influence on the overall circularity outcome (Ellen MacArthur Foundation, 2015).

The resulting pattern reflects the material logic of contemporary Swiss construction. Mineral fractions exhibit the lowest circularity performance because demolition processes still yield predominantly mixed aggregates that are down-cycled into low-value applications such as road base and backfilling (BAFU, 2015; Hollberg & Röck, 2023). Aluminium exhibits the highest circularity potential, as clean separation enables near closed-loop recycling with high substitution quality and limited functional degradation (Röck et al., 2020). Timber performs more modestly due to limited structural reuse, mechanical damage during dismantling, and the predominance of cascading end-of-life pathways (BAFU, 2018; Geraedts et al., 2019).

These material-specific limitations and improvement levers are synthesised in Table 4.2.B, which identifies the dominant circularity hotspots across the main building material systems and links them to their underlying causes and feasible improvement strategies under Swiss conditions. The table highlights that low value retention in mineral fractions is primarily driven by mixed demolition waste, that aluminium losses are associated with composite façade assemblies, and that timber circularity is constrained by structural reuse barriers and the absence of standardised reversible connections. Corresponding improvement potentials-such as selective dismantling, detachable assemblies, modular design, and high-purity robotic sorting-are supported by empirical evidence from Swiss practice and international studies.

Table 4.2.B. Circularity Hotspots and Improvement Potential.

Material System	Hotspot	Root Cause	Improvement Potential	Evidence Base
Concrete / aggregates	Low value retention (Q ≈ 0.3-0.5)	Downcycling; mixed demolition waste	Selective dismantling; reversible connections; high-purity sorting	BAFU 2015; Hollberg & Röck 2023
Aluminium façade systems	Purity loss from composite layers	Gaskets, coatings, insulation	Detachable assemblies; mono-material interfaces	Röck et al. 2020; EMF 2015
Timber	Low structural reuse rate	Mechanical damage; lack of standards	Modular assemblies; prefabrication; reversible fixings	BAFU 2018; Geraedts et al. 2019
Mixed mineral waste	Sorting losses	Manual sorting limits purity	Robotic EbiMIK sorting; digital tagging	Eberhard 2025
Building lifetime	Functional obsolescence	Layout/ Mechanical, Electrical and Plumbing (MEP) inaccessibility	Adaptable layouts; accessible routing; high ceilings	Volland et al. 2020

At building level, these material-specific behaviours result in a weighted MCI of approximately 0.42 for the Conventional building, which lies within the range reported for standard construction systems in European circularity studies (Ellen MacArthur Foundation, 2015; Röck et al., 2020). High-purity sorting increases this value to roughly 0.63 by improving substitution quality and reducing contamination losses, as demonstrated by robotic separation systems such as EbiMIK (Eberhard Unternehmungen, 2025). Extending the structural service life from 50 to 200 years in the Forever Home further elevates the index to approximately 0.75-0.80. This improvement is primarily driven by the utility factor U, which reduces the influence of linear material flows by increasing the functional output delivered per unit of material over time (Ellen MacArthur Foundation, 2015). Comparable levels of circularity are reported for long-life and reversible construction strategies in international literature (Durmisevic, 2019).

The interaction between circularity and service life can also be expressed through cumulative embodied impacts. For any material m, the cumulative cradle-to-gate impact over n rebuild cycles is given by:

Formula 4.2.8 - Cumulative embodied impact over multiple rebuild cycles
(Source: Author formulation based on circular life-cycle logic in Pomponi & Moncaster (2017), retained-value concepts from Ellen MacArthur Foundation (2015), and cumulative impact modelling in Göswein et al. (2021))

$$I_{\text{cum}} = \sum_{m} I_{\text{emb},m} \sum_{i=1}^{n} (1 - R_m S_m Q_m)^{\,i-1}$$

where $I_{\text{emb},m}$ denotes the embodied impact of material m associated with one construction cycle, n the number of construction cycles within the assessment horizon, and i the rebuild-cycle index. This formulation follows established circular life-cycle assessment approaches and illustrates how material recovery and value retention reduce cumulative impacts across successive lifetimes (Pomponi & Moncaster, 2017; Göswein et al., 2021).

To verify that the building-level implementation of the utility factor does not distort the comparative conclusions, a targeted sensitivity analysis is conducted using component-level service-life ranges derived from Swiss and international standards (ISO 15686-5, 2017; SIA 269). Structural concrete exhibits a decisive divergence between the Conventional building and the Forever Home, while façades, HVAC systems, and interior assemblies show negligible lifetime-related circularity gains due to repeated replacement cycles in both concepts. Recomputing the MCI using component-specific utility factors yields building-level values within the same numerical ranges as the simplified model, confirming that the adopted formulation is methodologically conservative and does not overstate lifetime-related circularity benefits.

Utility Factors and Circularity at Component Scale

The building-level utility factor (U) is used in the main MCI model to maintain consistency with the cradle-to-gate system boundary and to avoid speculative assumptions about component-specific replacement cycles (Ellen MacArthur Foundation, 2015). Nevertheless, it is important to verify whether a component-level implementation of the utility factor would materially influence the circularity results. This sensitivity analysis strengthens the methodological reliability of the approach by demonstrating that a more detailed formulation does not alter the comparative conclusions established earlier (Pomponi & Moncaster, 2017; Hollberg & Röck, 2023).

In principle, the MCI can be applied to individual building components by assigning each material system its own utility factor:

Formula 4.2.9 - Component-specific utility factor
(Source: Ellen MacArthur Foundation (2015); service-life definition consistent with ISO 15686-1 and ISO 15686-5)

$$U_m = \frac{t_{\text{actual},m}}{t_{\text{reference}}}$$

where $t_{\text{actual},m}$ denotes the actual service life of material or component m, and $t_{\text{reference}}$ the reference service life, set to 50 years in line with conventional Swiss office-building practice (SIA 269; Volland et al., 2020). Using the service-life ranges reviewed in Section 3.3.3, the following values are assumed under Swiss practice:

Structural concrete exhibits an actual service life of approximately 75-100 years in Conventional buildings and 200 years in the Forever Home, reflecting deliberate long-life structural design (Hollberg & Lenz, 2018; Volland et al., 2020). Façade systems typically achieve service lives of 30-50 years, HVAC systems 20-25 years, and interior timber assemblies 15-25 years, consistent with Swiss and European service-life data for non-structural building components (ISO 15686-5, 2017; Silva et al., 2021).

Because façades, HVAC systems, and interior assemblies undergo multiple replacement cycles within a 200-year horizon in both building concepts, their effective service life remains functionally similar across the two scenarios. Accordingly, the component-level utility factor for these non-structural elements remains approximately.

$$U_m \approx 1.0 (\text{façade, HVAC, interior timber; both concepts})$$

(Ellen MacArthur Foundation, 2015; ISO 15686-5, 2017).

By contrast, the structural system exhibits a decisive divergence. Using a 50-year reference life modelling convention, the utility factors for the primary load-bearing concrete become:

$$U_{\text{struct,conv}} = \frac{t_{\text{actual,struct,conv}}}{t_{\text{reference}}} = \frac{50}{50} = 1.0$$
$$U_{\text{struct,FH}} = \frac{t_{\text{actual,struct,FH}}}{t_{\text{reference}}} = \frac{200}{50} = 4.0$$

This reflects the design intent of the Forever Home, where the structural system is deliberately engineered for long-term adaptability and extended functional lifespan (Hollberg & Lenz, 2018; Durmisevic, 2019). In a component-level model, therefore, the longevity benefit is concentrated precisely in the elements with the highest material significance.

Recomputing the MCI with these component-specific utility factors reveals the same qualitative pattern as in the building-level formulation. Façade, HVAC, and interior timber components show no meaningful lifetime-related increase in circularity because neither concept achieves a 200-year service life for these elements. Structural concrete, by contrast, exhibits a strong utility uplift in the Forever Home, and this increase dominates the aggregated result. When the material-specific indices MCI_m are weighted by their respective mass contributions α_m, the building-level MCI is obtained as:

Formula 4.2.10 - Mass-weighted building-level Material Circularity Index
(Source: Ellen MacArthur Foundation (2015); building-scale application following Hollberg & Röck (2023))

$$\mathrm{MCI}_{\text{building}} = \sum_{m} \alpha_m \ \mathrm{MCI}_m$$

where:

- α_m is the mass share of material m in the total building material inventory,
- MCI_m is the material-specific circularity indicator.

The resulting building-level values remain within the same numerical ranges as the simplified model: approximately 0.42 for the Conventional building, 0.60-0.65 for the High-Purity scenario, and 0.72-0.78 for the Forever Home. The slight reduction relative to the main model (0.75-0.80) arises because the longevity benefit is attributed exclusively to structural concrete rather than uniformly across the entire building mass. This confirms that the building-level formulation used in the main analysis is methodologically conservative, avoiding overstatement of lifetime benefits while still capturing the dominant structural contribution (Pomponi & Moncaster, 2017; Hollberg & Röck, 2023).

The distribution of material masses provides a clear explanation for this behaviour. Structural concrete accounts for approximately 85-92 % of total building mass in both concepts, while façade systems contribute around 5-8 % and interior timber elements roughly 2-5 %, consistent with mass distributions reported for Swiss office buildings (KBOB, 2022; Hollberg & Lenz, 2018). For the Forever Home, central values of approximately 90 % structural concrete, 6 % façade assemblies, and 4 % interior timber are obtained from the mass model developed in Section 3.5. Because the MCI is aggregated as a mass-weighted average, the influence of shorter-lived components is naturally diluted in the building-level score. Even substantial differences in façade or HVAC replacement cycles therefore translate into only marginal shifts in the aggregated index, whereas changes in the utility factor of the structural system have orders-of-magnitude greater impact.

A parameter-level inspection further clarifies the role of recovery (R_m), substitution quality (S_m), and value retention (Q_m) in shaping component-level behaviour. Mineral fractions remain constrained by low value-retention coefficients ($Q_m \approx 0.3$-0.5) and limited substitution quality ($S_m < 0.4$), both of which persist across replacement cycles under current Swiss demolition practice (BAFU, 2015, 2018; Hollberg & Röck, 2023). Aluminium exhibits high circularity potential due to high recovery rates and near closed-loop substitution quality when cleanly separated (Röck et al., 2020), while timber performs more modestly because of limited structural reuse and predominantly cascading end-of-life pathways (BAFU, 2018; Geraedts et al., 2019). These parameter characteristics are largely independent of component lifespan, further explaining why component-level utility factors introduce only incremental changes at material scale and negligible changes at building scale.

To assess the robustness, referring to the ranking, of this conclusion, the component-level results were recalculated under a range of uncertainty conditions. Varying component lifetimes within the ranges specified in Section 3.3.3 and applying ±20 % variation to recovery and substitution parameters did not invert the ranking between the Conventional building, the High-Purity scenario, and the Forever Home. Even under pessimistic assumptions-such as façade lifetimes reduced to 25 years or lower aluminium recovery-the structural utility factor remains the dominant determinant of building-level circularity. This confirms that the simplified building-level model offers a stable and conservative representation of circularity performance without compromising analytical precision (Pomponi & Moncaster, 2017; Hollberg & Röck, 2023).

From a design perspective, the component-level analysis highlights that the greatest gains in circularity arise from durable structural systems that maintain high functional value over long time horizons and from recovery pathways that maximise substitution quality and retained material value (Durmisevic, 2019; Zijlstra, 2023). Incremental extensions of façade or HVAC service life have limited influence on overall circularity unless accompanied by fundamental changes in recoverability or material composition. This reinforces the strategic relevance of the Forever Home's long-lived structural frame and its compatibility with high-purity mineral sorting systems, which together deliver many circularity improvements observed in the analysis.

These findings also have direct implications for the economic evaluation in Section 4.3, where reduced replacement frequency of structural components and improved material recovery rates influence long-term embodied-cost trajectories. By reducing future demand for virgin materials and increasing recoverable value at end-of-life, the circularity characteristics quantified here feed directly into the circular life-cycle cost assessment that follows (Ellen MacArthur Foundation, 2015; Zijlstra, 2023).

4.3 Economic Assessment

The economic assessment applies the same cradle-to-gate (A1-A3) system boundary as the life-cycle assessment to isolate the embodied cost implications of material quantities, circularity performance, and service-life assumptions. This corresponds to the product stage of the building life cycle and excludes operational, maintenance, and end-of-life cash flows, which would require additional assumptions on user behaviour, energy prices, and refurbishment strategies that are not robust at the conceptual design stage (EN 16627, 2015; ISO 15686-5, 2017). Restricting the analysis to embodied material costs and replacement cycles ensures methodological consistency with the preceding environmental and circularity assessments and enables a transparent comparison of design alternatives.
Upfront embodied material costs are derived by combining the material intensities established in Section 3.5 with representative unit cost proxies based on publicly available Swiss and European market data. In construction practice, prices are typically reported per executed volume or area (e.g. CHF/m³ of concrete or CHF/m² of façade systems). For consistency with the mass-based life-cycle cost framework applied in this study, these prices are converted into mass-normalised unit costs using standard material densities and representative system masses. The resulting values are interpreted as system-level cost proxies that capture both material supply and typical execution requirements and are applied consistently across all building variants.

The derived embodied material costs for the Conventional reference building and the Forever Home are summarised in Table 4.3.A.

Table 4.3.A. Embodied material costs (A1-A3).

Material system	Unit cost (CHF/kg)*	Conventional mass (kg/m² GFA)	Forever Home mass (kg/m² GFA)	Embodied cost (CHF/m² GFA)	References
Reinforced concrete	0.25	1 200	1 500	300 / 375	Vigier Beton AG (2025); Holcim Schweiz AG (2025)
Structural timber (GL/CLT)	1.20	50	150	60 / 180	Binderholz GmbH (2023); Holzkurier (2025)
Aluminium-glass façade system	4.00	45	65	180 / 260	Houzy (2024); Jansen AG (2022); Schüco International KG (2022)
Total (A1-A3)	-	-	-	**540 / 815**	-

Table 4.3.A shows that the Forever Home exhibits higher upfront embodied costs per m² GFA than the Conventional reference building. This difference is structural rather than inefficient. The Forever Home intentionally incorporates increased material thicknesses, more robust assemblies, and higher façade mass to enable a 200-year service life, reversible construction, and high-quality material recovery. The resulting upfront cost premium therefore reflects deliberate long-life and circular design choices rather than over-specification.
At the same time, the table highlights that the cost increase is driven primarily by structural and envelope components, which dominate embodied impacts in both variants. This establishes the baseline for the subsequent long-term cost analysis, where differences in replacement frequency and circularity performance are evaluated over the full 200-year assessment horizon (Ellen MacArthur Foundation, 2015; Zijlstra, 2023).

To evaluate economic performance over a 200-year horizon, the embodied material costs are combined with the replacement cycles defined in Section 3.3.3. The Conventional building undergoes full structural renewal every 50 years, resulting in four replacement cycles within the assessment period. The High-Purity variant follows the same cycle structure but benefits from improved material recovery and substitution quality. In contrast, the Forever Home is designed for a single 200-year structural cycle, thereby avoiding repeated material replacement, which dominates long-term embodied costs in conventional construction. Cumulative costs are calculated using a discounted cash-flow formulation consistent with established life cycle costing standards (EN 16627, 2015; ISO 15686-5, 2017; RICS, 2016).

Formula 4.3.1 - Cumulative discounted embodied cost with circularity-adjusted replacement cycles
(Source: cost accumulation logic consistent with EN 16627 and ISO 15686-5; circularity and retained-value formulation aligned with Ellen MacArthur Foundation (2015))

$$C_{cum} = \sum_{m} \sum_{i=1}^{n} \left[C_{emb,m}(1 - S_m R_m Q_m) + C_{proc,m} R_m \right] \cdot \frac{1}{(1+r)^{t_i}}$$

with $C_{emb,m}$ denoting the material-specific embodied cost of one construction cycle, $C_{proc,m}$ the processing cost associated with recovery, r the real discount rate, replacement years $t_i = \{0,50,100,150\}$, and $n = 4$ for the Conventional and High-Purity buildings and $n = 1$ for the Forever Home. A real discount rate of $r = 2\%$ is adopted, which lies within the 2-3 % range commonly used in European building life-cycle cost assessments and is consistent with the ranges reported in recent LCC reviews (Cheng et al., 2023).

Table 4.3.B. Present-value embodied cost over a 200-year horizon (A1-A3 system boundary).

Scenario	Service life assumption	Replacement cycles (0-200 y)	Present Value (PV) cost (CHF/m² GFA)
Conventional	50 years	0, 50, 100, 150	**≈ 1 530**
High-Purity (EbiMIK)	50 years	0, 50, 100, 150	**≈ 1 290**
Forever Home	200 years	0 only	**≈ 820**

The present-value results in Table 4.3.B show that the initial cost hierarchy reverses over time. While the Forever Home is the most expensive option at year 0, it becomes the least costly option once the first avoided rebuild is considered and remains the lowest-cost strategy over the 200-year horizon. High-Purity design outperforms the Conventional scenario because improved recovery and substitution reduce the effective cost of each cycle, but it cannot compensate for the repeated structural renewals inherent in a 50-year service-life framework. This pattern is consistent with circular life-cycle cost modelling, where higher upfront investment in reversible and long-lived systems can yield lower discounted costs over long horizons (Zijlstra, 2023; Ellen MacArthur Foundation, 2015).
Circularity influences the economic model through the recovery (R_m), substitution quality (S_m), and value-retention (Q_m) parameters introduced in Section 4.2. These parameters determine the share of embodied material cost that is effectively retained across replacement cycles by reducing virgin-material demand and enabling higher-quality secondary material streams (BAFU, 2015, 2018; Eberhard, 2021; Zijlstra, 2023). At building scale, this effect can be represented through a simplified relationship linking circularity performance to the effective embodied cost per construction cycle:

Formula 4.3.2 - Circularity-adjusted effective embodied material cost
(Source: circularity-cost linkage conceptually derived from Ellen MacArthur Foundation (2015); economic interpretation consistent with EN 16627 and ISO 15686-5)

$$C_{eff} = C_{emb}(1 - \alpha \cdot MCI)$$

where C_{emb} denotes the embodied material cost of a single construction cycle and α is a dimensionless scaling coefficient that translates changes in the Material Circularity Index (MCI) into changes in retained economic value.

In this study, $\alpha \approx 0.6$is adopted as an empirically calibrated mid-range value. It is derived from the relative reduction in effective embodied cost observed between the building-level MCI values of approximately 0.42 (Conventional), 0.63 (High-Purity), and 0.75-0.80 (Forever Home) established in Section 4.2, and is consistent with the magnitude of cost-retention effects reported in recent circular life-cycle costing (C-LCC) studies (Zijlstra, 2023). Interpreted marginally, this formulation implies that a 0.10 increase in MCI corresponds to an average reduction of approximately 6 % in effective embodied cost per cycle.

In multi-cycle systems such as the Conventional and High-Purity buildings, this reduction compounds across successive replacement events, thereby moderating long-term material expenditure despite higher upfront costs. In the Forever Home, the circularity effect acts only once because repeated structural renewal is avoided; however, it interacts with the elimination of multiple replacement cycles, producing a disproportionately large reduction in cumulative embodied cost over the 200-year assessment horizon. This formulation therefore captures the combined economic influence of circularity (cost intensity per cycle) and longevity (number of cycles) without overstating the precision of circularity-cost coupling.

Table 4.3.C. Parameters used in the circularity-adjusted embodied cost model.

Parameter	Source / Justification	Range / Value
Discount rate r	SIA 2031 / EN 16627	2 % (real)
Cycles n	Conventional = 4 (50 a), Forever Home = 1 (200 a)	-
R_m, S_m, Q_m	From MCI (§ 4.2): concrete 0.11-0.36; aluminium 0.28-0.81; timber 0.05-0.22	-
Processing cost $C_{\text{proc},m}$	0.01-0.06 CHF/kg (Eberhard 2025; Empa 2021)	-
MCI influence coefficient α	Derived from ratio of retained cost between 0.42 → 0.63 MCI	≈ 0.6

The parameters summarised in Table 4.3.C define the cost dynamics within the circularity-adjusted embodied cost model. The ranges adopted for R_m, S_m, and $Q_m$match the empirical values used in the MCI analysis in Section 4.2 and are grounded in Swiss demolition practice, EbiMIK robotic high-purity sorting, and recent European construction LCA and circular-economy studies (BAFU, 2015, 2018; Eberhard, 2021; Röck et al., 2020; Zijlstra, 2023). Processing-cost assumptions of 0.01-0.06 CHF/kg reflect internal data from Eberhard's EbiMIK facility and lie within the cost ranges reported for mineral demolition-waste processing in Swiss and German-language practice reports. The discount rate is aligned with the LCC standards cited above (ISO 15686-5, 2017; EN 16627, 2015) and falls within the empirically observed range of discount rates used in building LCC case studies, where sensitivity analyses consistently identify $r$as one of the dominant drivers of present-value results (Cheng et al., 2023).

These results also permit a brief decoupling of longevity and circularity. A hypothetical variant of the Forever Home-retaining its 200-year design life but applying conventional recovery rates and substitution qualities-would already outperform both 50-year scenarios because the primary cost burden lies in repeated structural renewal. Circularity then acts as an additional modifier, reducing the effective cost of the single remaining cycle by lowering virgin-material demand and increasing retained value at each intervention. This distinction mirrors findings from C-LCC studies, where extended service life governs the number of cost events while circularity governs the cost intensity of each event (Zijlstra, 2023; Pomponi & Moncaster, 2017). Longevity therefore determines the frequency of embodied-cost cycles, whereas circularity determines their magnitude; their combined influence explains the substantial cost advantage of the Forever Home.

To express the comparative magnitude of long-term cost differences more transparently, the present-value results are normalised relative to the Conventional building using the standard percentage-difference formulation.

$$\Delta = \frac{C_{\text{scenario}} - C_{\text{Conv}}}{C_{\text{Conv}}}. \quad (4.3.3)$$

This normalisation isolates the proportional impact of increased circularity and extended service life, independent of absolute cost levels, and provides a consistent basis for assessing the economic effect of the underlying material and design assumptions. The resulting values are summarised in table 4.3.D.

Table 4.3.D. Relative cost reductions of alternative scenarios compared to the Conventional building.

Scenario	PV cost (CHF/m² GFA)	Difference vs Conventional (%)
Conventional	1 530	0% (baseline)
High-Purity (EbiMIK)	1 290	-16%
Forever Home	820	-46%

Substitution of the present-value costs from Table 4.3.D. yields $(2\,400 - 2\,850)/2\,850 \approx -0.158 (\approx -16\,\%)$ for the High-Purity scenario and $(1\,270 - 2\,850)/2\,850 \approx -0.554 (\approx -55\,\%)$ for the Forever Home. These values reflect the combined economic effect of reduced cost intensity per cycle-driven by higher circularity-and reduced cycle frequency in long-life designs. Similar magnitudes of long-term savings for circular and long-lived building concepts are reported in recent case studies and modelling exercises, confirming that the results lie within a plausible range (Ellen MacArthur Foundation, 2015; Zijlstra, 2023).

Sensitivity analysis confirms the structural robustness of the model. Financial parameters influence absolute values more strongly than technical parameters: increasing the discount rate reduces the long-term advantage of extended service life but does not alter the ranking between scenarios, in line with LCC sensitivity studies that identify the discount rate as a primary driver of result variability (Cheng et al., 2023). Technical circularity parameters, such as recovery and substitution rates, influence cost intensity within cycles but have limited effect on the comparative results because they act on all scenarios simultaneously, albeit to different extents. Market parameters, including processing and unit-material costs, shift absolute values but do not change the relative hierarchy as long as the proportional relationships between scenarios remain similar. Because the analysis excludes residual material value at year 200, the long-term advantage of the Forever Home is conservative; a design with high circularity and high material purity would retain non-negligible residual value at the end of the analysis horizon even though this is not captured numerically in the A1-A3 boundary (EN 16627, 2015; Zijlstra, 2023).
Finally, the economic dynamics demonstrated here scale proportionally with building size and typology. Because structural renewal dominates long-term embodied expenditure, larger buildings or portfolios would exhibit even stronger absolute cost differences between short- and long-life designs, while the percentage savings remain structurally similar (Pomponi & Moncaster, 2017; Zijlstra, 2023). Circularity modifies cost intensity at the material level, meaning that improvements in recovery and substitution yield proportional benefits regardless of gross floor area. This scaling behaviour is directly relevant for the discussion in Chapter 5, where the economic significance of durability and circularity is assessed at portfolio and industry level and linked back to policy instruments and investment strategies that encourage long-life, high purity building concepts.

5 Discussion

The results of this study directly address the central research question of whether long-life building concepts can outperform conventional Swiss office buildings when environmental, circularity, and economic performance are assessed consistently over extended service horizons. Across all three assessment dimensions, the findings demonstrate that assumed service life is the dominant determinant of sustainability performance, outweighing differences in material efficiency, recycling performance, or upfront cost intensity.

From an environmental perspective, the higher upfront embodied greenhouse-gas emissions, primary-energy demand, and material costs of the Forever Home arise directly from its underlying design logic. Larger structural spans, increased storey heights, and more robust load-bearing systems are required to enable long-term adaptability and future changes in use without major structural intervention. These design choices inevitably increase initial material quantities and, consequently, cradle-to-gate impacts. The results therefore confirm that long-life construction involves a deliberate front-loading of environmental and economic investment and cannot be assessed fairly using short-term indicators or fixed reference periods, as commonly applied in building life-cycle assessments (ISO 15686-1; EN 15978; Hollberg et al., 2022).

When impacts are evaluated over extended service lives, however, this initial disadvantage is reversed. Lifetime-normalised results show that beyond a service life of approximately 80-100 years, the Forever Home performs better than the conventional reference building across all environmental indicators. Over a 200-year horizon, annualised embodied greenhouse-gas emissions are substantially lower. This behaviour reflects the non-linear relationship between service life and cumulative embodied impacts documented in long-term building LCA studies (Hollberg & Lenz, 2018; Röck et al., 2020). It indicates that repeated demolition and reconstruction cycles, rather than initial construction, dominate cumulative environmental burdens in conventional buildings. Consequently, assessment approaches based on fixed or short reference periods systematically underestimate the environmental benefits of durability-oriented construction strategies.

The material-level results explain this effect in greater detail. Structural concrete and façade systems account for more than 90 % of cradle-to-gate impacts in both building concepts, while timber-despite its architectural and symbolic relevance-contributes only a minor share of total A1-A3 emissions under Swiss construction conditions. This confirms that reducing the frequency with which large mineral material stocks are replaced has a far greater influence on long-term environmental performance than marginal reductions in material quantities or selective material substitution. Extending the service life of the primary structural system therefore exerts a substantially stronger effect than improvements applied to lighter or short-lived components.

This interpretation is reinforced by the sensitivity analysis of component service lives. Extending the lifetimes of façades, HVAC systems, or interior elements leads to only minor changes in building-level embodied impacts and circularity outcomes. While flexible technical systems remain essential for maintaining functionality over time, their comparatively low mass share limits their influence on cumulative impacts. Adaptability measures are therefore only environmentally effective when coupled with a structural system explicitly designed for long-term use. Adaptability alone does not prevent material turnover if the load-bearing structure itself is not intended to remain in service.

The Material Circularity Index results further highlight the central role of service life. Improvements in sorting quality and recycling technology-such as high-purity robotic separation-significantly increase circularity relative to current Swiss practice. However, when building lifetimes remain short, the achievable improvement remains limited. Substantially higher circularity values are attained only when extended structural service life is incorporated through the utility factor. This finding supports circular-economy theory, which emphasises “slowing loops” through prolonged use over “closing loops” through end-of-life recycling alone (Ellen MacArthur Foundation, 2015; Pomponi & Moncaster, 2017). In the construction sector, circularity is therefore constrained primarily by how long materials remain in productive use, rather than by recycling performance at the point of demolition.

The economic assessment follows the same structural logic. Although the Forever Home exhibits higher upfront embodied costs, it yields the lowest discounted life-cycle cost over a 200-year horizon. The decisive factor is the avoidance of repeated structural replacement. High-purity recycling improves the cost performance of conventional buildings by reducing effective material input per cycle, but it cannot compensate for the long-term cost burden associated with recurring demolition and reconstruction. These results confirm that minimising initial construction costs does not necessarily minimise long-term expenditure at building or portfolio scale, a conclusion consistent with recent circular life-cycle costing studies (Zijlstra, 2023; Pomponi & Moncaster, 2017).

Taken together, the findings reveal a structural mismatch between prevailing assessment frameworks and long-term sustainability objectives. Common LCA, circularity, and cost benchmarks rely on static system boundaries and implicitly assume limited building lifetimes, typically in the range of 50-60 years. This systematically favours designs optimised for short-term performance and disadvantages concepts that aim to reduce cumulative material turnover through durability and adaptability. The results indicate that sustainability assessment in the construction sector should place greater emphasis on service life, structural permanence, and lifetime-normalised indicators, particularly for public buildings and long-term infrastructure.

Within this context, the Forever Home should be understood as an analytical reference rather than a fixed design solution. Its purpose is not to prescribe a single architectural outcome, but to demonstrate quantitatively how extended structural service life reshapes environmental, circularity, and economic performance when assessed consistently. The results show that longevity is not merely a qualitative design aspiration but a measurable and influential strategy for reducing cumulative environmental impacts and long-term material demand in the Swiss construction sector. At the same time, the analysis exposes methodological and institutional constraints within current design and assessment practices that limit the effectiveness of such strategies.

5.1 Recommendations & Outlook

The findings of this thesis carry several implications for construction practice, policy, and future research. At an industry level, the results demonstrate that durability-oriented design strategies are not inherently inefficient but are systematically disadvantaged by prevailing assessment frameworks. Cradle-to-gate benchmarks and short reference horizons favour low-mass, short-life construction even when such buildings impose higher cumulative environmental and economic burdens over time. Practitioners and developers should therefore interpret standard LCA and cost benchmarks with caution and explicitly account for service-life assumptions when comparing design alternatives.

From a policy perspective, the results suggest that current regulatory and certification frameworks insufficiently reward long-life construction. Swiss and European assessment standards could be strengthened by incorporating lifetime-normalised indicators alongside absolute A1-A3 values, particularly for public or long-term assets. Planning instruments that implicitly assume functional obsolescence after a few decades risk locking in structurally suboptimal building stocks. Incentivising adaptable layouts, increased storey heights, and reversible structural systems could therefore yield disproportionate long-term benefits without requiring radical material substitution.

At the same time, the Forever Home concept raises questions regarding compatibility with existing Swiss legal and regulatory structures. Current planning and building regulations generally require a clearly defined use category-such as residential, office, educational, or healthcare-with corresponding requirements for fire safety, accessibility, noise protection, and technical installations. A building explicitly designed for long-term adaptability and multiple future uses may not align neatly with a single predefined category at the time of approval. While this does not constitute a fundamental legal barrier, it may complicate permitting procedures and constrain design flexibility if compliance is assessed strictly against an initial use. Addressing this tension may require procedural adaptations, such as broader use definitions, staged approvals, or performance-based compliance approaches that prioritise structural capacity and envelope performance over fixed programmatic use.

The circularity analysis further indicates a need for strategic prioritisation. Continued investment in high-purity sorting technologies is justified and effective, but such technologies alone cannot deliver high circularity at building scale if structures remain short-lived. Circular-economy strategies in construction should therefore shift emphasis from end-of-life optimisation toward service-life extension and structural reuse. In practice, this implies prioritising spatial neutrality, accessible service routing, and long-term adaptability over incremental improvements in recycling rates, while recognising that regulatory frameworks may influence the extent to which flexibility can be realised.

Methodologically, the study highlights the importance of aligning system boundaries across environmental, circularity, and economic assessments. Applying a building-level utility factor proved to be a conservative and robust approach, capturing the dominant influence of structural longevity while avoiding speculative assumptions about component-level replacement. Future research could refine this approach by integrating selective component-level modelling where empirical data are available, particularly for façade systems and technical installations.

Several limitations point toward further research needs. Operational energy was treated as a benchmark rather than through dynamic simulation, which is appropriate at a conceptual design stage but could be refined in future work using building-physics models. End-of-life processes were represented through circularity parameters rather than explicit LCA modules; detailed modelling of demolition, reuse, and substitution pathways would strengthen the link between circularity and environmental outcomes. Finally, the analysis focused on office buildings under Swiss conditions. Extending the framework to residential typologies, infrastructure, or different climatic contexts would test the generalisability of the findings and allow regulatory implications to be assessed across a broader range of building types.

Overall, the discussion demonstrates that longevity is not a secondary design attribute but a central determinant of sustainability in mineral-intensive construction. When service life is treated explicitly and consistently across environmental, circularity, and economic assessments, durable building concepts emerge as a credible-and under many conditions superior-approach for reducing cumulative environmental impacts, improving material circularity, and lowering long-term costs in the Swiss construction sector. These insights provide a coherent basis for the concluding chapter, which synthesises the key findings and distils their implications for design practice, assessment frameworks, and future research.

6 Conclusions

This thesis investigated how assumed service life influences the environmental, circularity, and economic performance of building concepts under Swiss construction conditions. The objective was to assess whether durability-oriented buildings can outperform conventional construction when evaluated using consistent system boundaries and extended time horizons. This addresses a central gap in current sustainability assessment practice, where short reference periods and cradle-to-gate benchmarks dominate despite the long-lived nature of the building stock. To this end, a comparative assessment framework was applied to two analytically defined office buildings: a conventional reference building representative of current practice and a durability-oriented Forever Home designed for long-term adaptability and extended structural service life. Environmental impacts, material circularity, and embodied costs were assessed using harmonised assumptions, allowing the influence of service life to be isolated from material substitution effects and optimistic end-of-life scenarios.

The results show that assumed service life is the dominant determinant of sustainability performance in mineral-intensive construction. The Forever Home exhibits higher upfront embodied emissions, energy demand, and material costs due to its robust structural design and increased material quantities. When assessed over short reference periods, this leads to inferior performance compared to the conventional building. When impacts are normalised over extended service lives, however, this relationship reverses. Beyond approximately 80-100 years of use, the Forever Home consistently outperforms the conventional reference across all environmental indicators, with substantially lower annualised embodied impacts over a 200-year horizon.

Material-level analysis explains this behaviour. Structural concrete and façade systems account for many cradle-to-gate impacts in both buildings, while lighter components and material substitutions play a secondary role. Sensitivity analyses confirm that extending the service life of non-structural components yields only minor benefits unless the primary structure itself is designed for long-term use. Adaptability measures are therefore environmentally effective only when combined with structural permanence. The circularity assessment reinforces this conclusion. Improvements in sorting quality and recycling technology increase circularity relative to current practice, but their effect remains limited when building lifetimes are short. High circularity values are achieved primarily through extended service life, which reduces replacement frequency and slows material flows. Circularity in construction is thus constrained more by how long materials remain in use than by end-of-life recycling performance alone. The economic assessment follows the same pattern. Although the Forever Home entails higher upfront embodied costs, it achieves the lowest discounted life-cycle cost over extended time horizons due to the avoidance of repeated structural replacement. Improvements in recycling performance reduce costs for conventional buildings but do not offset the long-term cost burden associated with recurring demolition and reconstruction.

The results reveal a systematic mismatch between prevailing sustainability assessment frameworks and long-term sustainability objectives, as current benchmarks implicitly assume limited building lifetimes and therefore favour designs optimised for short-term performance while undervaluing durability-oriented construction. Within this context, the Forever Home serves as an analytical archetype that demonstrates how explicitly accounting for service life reshapes environmental, circularity, and economic outcomes, showing that longevity is not a secondary design attribute but a central determinant of sustainability in mineral-intensive construction. When service life is treated explicitly and consistently, durable building concepts emerge as a credible-and under many conditions superior-pathway toward reducing cumulative environmental impacts, improving material circularity, and lowering long-term costs in the Swiss construction sector.

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8 Appendix

8.1 Appendix A. Declaration of the use of AI-based tools

AI-Based Tool	Use Case	Scope	Remarks
perplexity Last date of access: 04.12.2024	Spell-checking and re-writing of text	Entire work	
ChatGPT 4.0 Last date of access: 04.12.2024	Spell-checking and re-writing of text	Entire work	

8.2 Appendix B - Reference Tables for Chapter 3.3

This appendix contains the detailed data tables supporting the quantitative assumptions applied in Chapter 3.3 and the modelling framework in Chapter 4. Tables are grouped by indicator type for clarity. All values follow the boundary conditions A1-A3 unless otherwise stated.

Table B.1. Embodied Carbon and Energy Benchmarks for Swiss Office Buildings

Source	Scope / Building Type	GWP (kg CO_2-eq/m^2, A1-A3)	Embodied Energy (GJ/m^2)	Notes
Model result (this thesis)	Swiss reinforced-concrete office, conventional	**600-850**	**4.5-6.0**	Calculated using KBOB 2009/1:2022 A1-A3 material factors applied to reference quantities.
Hollberg & Lenz (2018)	Swiss building-stock model	600-850	4.5-6.0	Includes service-life effects and refurbishment cycles; used to validate modelling range.
Röck et al. (2020)	Meta-analysis of 650 EU buildings	Median ≈760; IQR ≈570-940	-	Confirms Swiss values lie near EU median for office-type buildings.
One Click LCA (2023)	Global benchmark database	≈900 ± 300	-	Used only for contextual comparison; excluded from modelling due to inconsistent system boundaries (A-D).

Model assumption:
Baseline embodied GWP for the conventional case is **600-850 kg CO_2-eq/m^2 (A1-A3)**.
The Forever Home assumes **+10-20 % higher upfront embodied GWP**, consistent with increased structural robustness and durability-oriented design.
Primary sources

- KBOB, ecobau, IPB. (2022). *Ökobilanzdaten im Baubereich, Datenstand 2009/1:2022*. Zürich.
  → Provides **material-level A1-A3 factors** used in the building model.
- Hollberg, A., & Lenz, B. (2018). *Environmental performance of buildings: What is the influence of the assumed service life? Building Research & Information*, 46(6).
  → Swiss stock-based validation of embodied-impact ranges.

Table B.2. Operational-Energy Benchmarks for Office Buildings

Source	Reference Standard / Data Type	Energy Use (kWh/m²·a)	Context
Swiss benchmark range (literature synthesis)	Office buildings, CH	**45-60**	Range consistent with SIA-based calculations and Swiss case studies.
Minergie-A (2021)	Office category requirements	≤55	Upper bound for high-performance envelopes (office-specific category).
2226 Building (Lustenau)	Measured case study	≈50-55	Demonstrates feasibility of low-tech, passively stabilised operation.
EU Level(s) Framework (2021)	EU-wide median	≈70	Included for contextual comparison only.

Model assumption:
Both cases are modelled at **45-55 kWh/m²·a**, with the lower bound applied to the Forever Home to reflect thermal-mass stability rather than mechanical optimisation.

Primary sources

- SIA. (2016). *SIA 380/1: Thermische Energie im Hochbau*. Zürich.
- Minergie. (2021). *Minergie-A Anforderungen - Bürogebäude*.
- Lechner, N., & Eberle, D. (2013). *2226 - Architecture for energy efficiency*. Birkhäuser.

Table B.3. Influence of Lifetime on Annualised Embodied Impacts

Study	Assumed Lifetimes (yrs)	Effect on Annualised GWP	Comment
Hollberg et al. (2022)	40-120	≈−35 % (50→100)	Strong reduction up to ~100 yrs; diminishing returns thereafter.
Röck et al. (2020)	50-100; extrapolated to 200	≈−25 % to −40 % (50→100); max ≈−45 %	Non-linear lifetime sensitivity.
Pomponi & Moncaster (2017)	50-100	≈−30 % (50→100)	Effects saturate beyond ~100 yrs.

Model implication:
Extending service life from **50→100 years reduces annualised GWP by ~30-40 %**; extension to **200 years yields total reductions of ~40-45 %**.

Table B.4. Material-Level Emission and Energy Factors (A1-A3)

Material	Source	GWP (kg CO_2-eq/kg)	Energy	Notes
Concrete (CEM II/B)	KBOB 2009/1:2022	**0.089**	**0.175 kWh oil-eq/kg**	Swiss average high-rise concrete (no reinforcement).
	ecoinvent v3.9 (CH)	≈0.10	-	Used only for plausibility check.
Timber (excl. biogenic credit)	KBOB 2009/1:2022	≈0.10	-	Allocation consistent with EN 15804+A2.
Aluminium profiles / sheets	KBOB 2009/1:2022	**≈5.6-5.7**	-	Stock aluminium products; no façade-system aggregation.

Model assumption:
All material emissions are calculated using **KBOB factors**; no “averaged façade system” factors are used unless explicitly defined.

Table B.5. Component Service-Life Expectations

Component	Typical Lifetime (yrs)	Source	Notes
Primary concrete structure	75-100	SIA 269; ISO 15686-1	Structural durability under normal exposure.
Façade / glazing systems	30-50	Silva et al. (2021)	Dominant renewal driver.
HVAC systems	20-25	ISO 15686-5	Shortest technical lifespan.
Interior finishes	15-25	Case-study literature	Minor mass contribution.

Model assumption:
Utility factor applied at **whole-building scale** (50 yrs conventional; 200 yrs Forever Home).

Table B.6. Life-Cycle Cost Benchmarks (100-Year Horizon)

Source	Discount Rate	Net Present Value (NPV) (CHF/m²)	Notes
Röck et al. (2020)	3 %	≈2 400-2 800	EU-wide LCC synthesis; used for plausibility.
Model result (this thesis)	**2 %**	**≈2 600-2 800**	Derived from Swiss cost references and maintenance assumptions.

Methodological sources

- ISO 15686-5 (2017) - Life-cycle costing
- EN 16627 (2017) - Economic performance of buildings

Table B.7. Circularity and Material-Retention Indicators

Framework	Definition	Typical Values	Scope
Ellen MacArthur Foundation (2015)	Material Circularity Indicator (MCI)	0.35-0.45 (conventional); 0.65-0.80 (circular)	Method definition; ranges reflect case-study practice.
Durmisevic (2019)	Reversibility / disassembly index	0-1	Component level.
Hollberg et al. (2022)	Material retention over service life	Qualitative support	Building level.

Model assumption:
MCI = **0.4** (conventional); **0.7** (Forever Home).

8.3 Appendix C -Mass-Modelling Method

This appendix documents the calculation steps used to derive the material intensities applied in Chapter 4. All quantities are derived directly from building geometry and standard Swiss reference densities, ensuring transparency and consistency with the methodological framework of the life-cycle assessment.

C.1 Modelling Procedure

Geometric basis

For each building, material volumes are derived from simplified geometric representations based on gross floor area (GFA):

Slab volume

$$V_{\text{slab}} = t_{\text{slab}} \cdot A_{\text{floor}}$$

Vertical structural system represented as an equivalent thickness

$$V_{\text{vert}} = t_{\text{vert,eq}} \cdot A_{\text{floor}}$$

Façade area

$$A_{\text{façade}} = \text{perimeter} \cdot \text{storey height}$$

Façade mass is subsequently normalised by gross floor area (GFA) to ensure comparability between buildings with different geometries.

Volume-to-mass conversion
Material volumes are converted to mass using standard Swiss reference densities and KBOB façade mass ranges:

Reinforced concrete

$$\rho_{\text{conc}} = 2\,400 \text{ kg/m}^3 \text{(KBOB 2009/1:2022)}$$

Timber (CLT / GLULAM)

$$\rho_{\text{timber}} = 480 \text{ kg/m}^3 \text{(typical Swiss engineering value)}$$

Façade assemblies (aluminium-glass systems)

$$m'_{\text{façade}} = 60\text{-}120 \text{ kg/m}^2_{\text{façade area}} \text{(KBOB 2009/1:2022)}$$

The mass intensity per square metre of GFA is calculated as:

$$m_i = \frac{V_i \cdot \rho_i}{A_{\text{GFA}}}$$

Geometric differentiation between building concepts
The Forever Home differs from the conventional building through:

- increased slab thickness,
- slightly larger equivalent vertical structural thickness,
- higher façade-to-GFA ratio due to increased storey heights,
- increased timber quantities resulting from reversible and modular interior assemblies.

All differences arise from **geometry and spatial layout**, not from altered material properties or performance assumptions.

C.2 Calculation of Material Intensities
Concrete
The concrete mass per square metre of GFA is derived using the general relation:

$$m_{\text{conc}} = \rho_{\text{conc}}\left(t_{\text{slab}} + t_{\text{vert,eq}}\right)$$

- **Conventional building**

$$t_{\text{slab}} = 0.30 \text{ m}, t_{\text{vert,eq}} = 0.20 \text{ m}$$
$$m_{\text{conc,conv}} = 2\,400 \times (0.30 + 0.20) = 2\,400 \times 0.50 = 1\,200 \text{ kg/m}^2$$

- **Forever Home**

$$t_{\text{slab}} = 0.40 \text{ m}, t_{\text{vert,eq}} = 0.225 \text{ m}$$
$$m_{\text{conc,FH}} = 2\,400 \times (0.40 + 0.225) = 2\,400 \times 0.625 = 1\,500 \text{ kg/m}^2$$

Timber

Timber intensities are specified based on the extent of interior layers:

- **Conventional building (non-reversible interior fit-out):**

$$m_{\text{timber,conv}} = 50 \text{ kg/m}^2$$

- **Forever Home (reversible modular assemblies):**

$$m_{\text{timber,FH}} = 150 \text{ kg/m}^2$$

These values lie within the empirical Swiss range for interior and hybrid timber systems reported in SIA 279 and stock-based studies.

Façade

Façade mass per square metre of GFA is calculated as:

$$m_{\text{façade}} = \left(\frac{A_{\text{façade}}}{A_{\text{GFA}}}\right) \cdot m'_{\text{façade}}$$

- **Conventional building**

$$\frac{A_{\text{façade}}}{A_{\text{GFA}}} \approx 0.55, m'_{\text{façade}} \approx 85 \text{ kg/m}^2$$
$$m_{\text{façade,conv}} \approx 0.55 \times 85 \approx 45 \text{ kg/m}^2$$

- **Forever Home**

$$\frac{A_{\text{façade}}}{A_{\text{GFA}}} \approx 0.66, m'_{\text{façade}} \approx 98 \text{ kg/m}^2$$
$$m_{\text{façade,FH}} \approx 0.66 \times 98 \approx 65 \text{ kg/m}^2$$

C.3 Summary of Adopted Material Intensities

Material system	Conventional (kg/m²)	Forever Home (kg/m²)
Concrete	1 200	1 500
Timber	50	150
Façade	45	65

These material intensities are applied consistently in the embodied-impact (A1-A3), circularity, and life-cycle cost calculations presented in Chapter 4.

8.4 Appendix D Table D.1 - Summary of Chosen Material Values and Justifications

Parameter	Value	Applied To	Justification
Slab thickness	0.30 m / 0.40 m	Conv / FH	0.28-0.32 m typical for Swiss RC slabs (SIA practice); 0.40 m aligns with tall-storey adaptable structures and long-life precedents.
Concrete intensity	1 200 / 1 500 kg/m²	Conv / FH	Within KBOB Annex C range (2 000-2 800 kg/m² total RC mass). Higher FH value reflects thicker slabs + larger spans.
Equivalent vertical thickness	0.20 / 0.225 m	Conv / FH	Back-calculated from target intensities; matches typical Swiss hidden structural volume for offices (≈ 0.18-0.25 m).
Timber density	480 kg/m³	Both	GLT/CLT average from SIA 279 and Swiss manufacturers.

Parameter	Value	Applied To	Justification
Timber intensity	50 / 150 kg/m²	Conv / FH	Conv = low hybrid share; FH = high reversible interior structure (NEST, UMAR, YOND benchmarks).
Façade/GFA ratio	0.55 / 0.66	Conv / FH	Derived from building perimeters and storey heights; FH has wider footprint + taller floors → larger ratio.
Façade mass	45 / 65 kg/m² GFA	Conv / FH	Corresponds to 80-100 kg/m² façade assemblies typical in Swiss aluminium-glass systems.
GWP factors	Concrete: 0.09; Timber: 0.10; Façade: 1.50 kg CO_2/kg	Both	KBOB 2022 values reflecting Swiss electricity mix, CEM II/B cement and secondary aluminium.
Lifetimes	50 / 100 years	Conv / FH	Consistent with SIA 269 durability assumptions; FH explicitly designed for >100 years adaptability.

8.5 Appendix E - LCA Calculation Basis (A1-A3)

This appendix documents the numerical procedures used to derive the embodied greenhouse-gas emissions and primary-energy demand reported in Chapter 4. All calculations follow the Life Cycle Assessment (LCA) framework defined in **ISO 14040 and ISO 14044** and the **A1-A3 product-stage system boundary** defined in **EN 15804+A2**. Material masses originate from **Appendix C**, and emission and energy factors are taken from **KBOB 2009/1:2022**.

E.1 Calculation of A1-A3 Greenhouse-Gas Emissions (kg CO_2/m²)

For each material system *i*, cradle-to-gate greenhouse-gas emissions are calculated as:

$$\mathrm{GWP}_i = m_i \cdot f_{i,\mathrm{GWP}}$$

where

m_i= material mass per m² GFA (Appendix X),

$f_{i,\mathrm{GWP}}$= KBOB A1-A3 emission factor (kg CO_2/kg) (KBOB, 2022).

- **Y.1.1 Conventional building**
- $\mathrm{GWP}_{\mathrm{conc}} = 1200 \cdot 0.09 = 108.0$
- $\mathrm{GWP}_{\mathrm{timber}} = 50 \cdot 0.10 = 5.0$
- $\mathrm{GWP}_{\mathrm{façade}} = 45 \cdot 1.50 = 67.5$

$$\mathrm{GWP}_{\mathrm{tot,conv}} = 108.0 + 5.0 + 67.5 = 180.5 \text{ kg } CO_2/m^2$$

- **E.1.2 Forever Home**
- $\mathrm{GWP}_{\mathrm{conc}} = 1500 \cdot 0.09 = 135.0$
- $\mathrm{GWP}_{\mathrm{timber}} = 150 \cdot 0.10 = 15.0$
- $\mathrm{GWP}_{\mathrm{façade}} = 65 \cdot 1.50 = 97.5$

$$\mathrm{GWP}_{\mathrm{tot,FH}} = 135.0 + 15.0 + 97.5 = 247.5 \text{ kg } CO_2/m^2$$

These values correspond exactly to those reported in Chapter 4.

E.2 Calculation of A1-A3 Primary Energy Demand (MJ/m²)

Primary-energy demand is calculated as:

$$E_i = m_i \cdot f_{i,\mathrm{PE}}$$

where $f_{i,\mathrm{PE}}$is the KBOB primary-energy factor (MJ/kg) (KBOB, 2022).

- **E.2.1 Conventional building**

- $E_{\text{conc}} = 1200 \cdot 0.85 = 1020$
- $E_{\text{timber}} = 50 \cdot 2.30 = 115$
- $E_{\text{façade}} = 45 \cdot 12.0 = 540$

$$E_{\text{tot,conv}} = 1020 + 115 + 540 = 1675 \text{ MJ/m²}$$

- **E.2.2 Forever Home**
- $E_{\text{conc}} = 1500 \cdot 0.85 = 1275$
- $E_{\text{timber}} = 150 \cdot 2.30 = 345$
- $E_{\text{façade}} = 65 \cdot 12.0 = 780$

$$E_{\text{tot,FH}} = 1275 + 345 + 780 = 2400 \text{ MJ/m²}$$

E.3 Biogenic Carbon Storage in Timber (EN 15804+A2)

Biogenic carbon is reported separately in accordance with **EN 15804+A2** and is not credited within A1-A3.

Step 1: Oven-dry mass

$$m_{\text{dry}} = \frac{m_{\text{tim}}}{1.12}$$

(Conversion factor from installed to oven-dry timber: Hischier et al., 2021.)

Step 2: Stored CO_2

$$\text{CO}_{2,\text{stored}} = m_{\text{dry}} \cdot 1.833$$

where **1.833 kg CO_2/kg dry wood** reflects stoichiometric carbon conversion (EN 15804+A2; Hischier et al., 2021).

- **E.3.1 Conventional building**

$$m_{\text{dry}} = 50/1.12 = 44.64$$
$$\text{CO}_{2,\text{stored}} = 44.64 \cdot 1.833 = 81.7 \text{ kg CO₂/m²}$$

- **E.3.2 Forever Home**

$$m_{\text{dry}} = 150/1.12 = 133.93$$
$$\text{CO}_{2,\text{stored}} = 133.93 \cdot 1.833 = 245.1 \text{ kg CO₂/m²}$$

E.4 Annualisation of Embodied GWP

Annualised embodied impact is computed as:

$$\text{GWP}_{\text{ann}} = \frac{\text{GWP}_{\text{tot}}}{L}$$

where $L$is the assumed service life, following **ISO 15686-5** conventions.

- Conventional building (50 years):

$$180.5/50 = 3.61 \text{ kg CO₂/(m²\cdotpa)}$$

- Forever Home (200 years):

$$247.5/200 = 1.24 \text{ kg CO₂/(m²\cdotpa)}$$

E.5 Contribution Analysis

Material shares are calculated as:

$$s_i = \frac{\text{GWP}_i}{\text{GWP}_{\text{tot}}}$$

Conventional building

- Concrete: 59.8 %
- Façade: 37.4 %

- Timber: 2.8 %

Forever Home

- Concrete: 54.5 %
- Façade: 39.4 %
- Timber: 6.1 %

These proportions confirm established European and Swiss LCA patterns, where concrete and façade systems dominate A1-A3 impacts (Röck et al., 2020; KBOB, 2022).

E.6 Sensitivity Calculations (Table 4.1.2)

Following ISO 14040 guidance for parameter variation:

- Concrete ±10 %
  - Conventional: ±10.8 kg
  - Forever Home: ±13.5 kg
- Façade +10 %
  - Conventional: +6.75 kg
  - Forever Home: +9.75 kg
- Timber +20 %
  - Conventional: +1.0 kg
  - Forever Home: +3.0 kg

E.7 Lifetime Sensitivity (ISO 15686-5)

Alternative service lives use:

$$\mathrm{GWP}_{\mathrm{ann}} = \frac{\mathrm{GWP}_{\mathrm{tot}}}{L}$$

Examples:

- Conventional:
  40 y → 4.51; 50 y → 3.61
- Forever Home:
  100 y → 2.48; 150 y → 1.65; 200 y → 1.24

Appendix E Summary

All numerical results reported in Chapter 4 are fully traceable to:

- material intensities defined in **Appendix C**,
- emission and energy factors from **KBOB 2009/1:2022**,
- biogenic-carbon accounting rules from **EN 15804+A2**,
- lifetime modelling conventions from **ISO 15686-5**,
- calculation structures defined in **ISO 14040/14044** and peer-reviewed LCA literature (Hollberg & Lenz, 2018; Röck et al., 2020).

This appendix ensures complete methodological transparency and reproducibility of the LCA results.

8.6 Appendix F - Material Circularity Index (MCI) Calculation Basis

This appendix documents the equations and aggregation steps used to derive the material- and building-level circularity results presented in Section 4.2. The methodology follows the **Material Circularity Indicator (MCI) framework developed by the Ellen MacArthur Foundation (2015)**. This framework is **operationalised for Swiss construction practice** using empirically observed recovery and sorting outcomes reported in Swiss waste statistics (BAFU, 2015, 2018), early-market high-purity sorting data (Eberhard Unternehmungen, 2025), and recent European research on circular construction systems (Röck et al., 2020; Hollberg & Röck, 2023).

F.1 Material-Level MCI Formulation

Following the **Circularity Indicators methodology** (Ellen MacArthur Foundation, 2015), the Material Circularity Indicator for a material *m* is defined as a function of the **Linear Flow Ratio (LFR)** and the **utility factor (U)**:

Linear Flow Ratio (LFR)

(Source: Ellen MacArthur Foundation, 2015)

$$\mathrm{LFR} = 1 - \frac{V + W}{2M}$$

Utility factor (U)

(Source: Ellen MacArthur Foundation, 2015; service-life definitions per ISO 15686)

$$U = \frac{t_{\text{actual}}}{t_{\text{reference}}}$$

Material Circularity Indicator

(Source: Ellen MacArthur Foundation, 2015)

$$\mathrm{MCI}_m = 1 - \mathrm{LFR}(1 - U)$$

where:

- V is the mass of virgin material input,
- W is the mass of material not recovered at end-of-life,
- M is the total material mass flow,
- t_{actual} is the achieved service life, and
- $t_{\text{reference}}$ is the reference service life.

Rewriting LFR using Swiss recovery conditions

Swiss demolition statistics do not report V and W directly in the form required by the MCI framework. Instead, empirical recovery behaviour is described through **recovery rates, quality losses, and down-cycling pathways** (BAFU, 2015, 2018; Hollberg & Röck, 2023). These observed outcomes are therefore **operationalised** using the following analytical parameters:

- R_m: recovery rate at end-of-life
- S_m: substitution quality of recovered material
- Q_m: retained technical value after processing

Virgin material share

(Author formulation following Ellen MacArthur Foundation (2015); parameterised using Swiss demolition data from BAFU (2015, 2018) and Hollberg & Röck (2023))

$$\frac{V}{M} = 1 - R_m S_m Q_m$$

Unrecovered material share

(Author formulation following Ellen MacArthur Foundation (2015); calibrated using Swiss waste statistics)

$$\frac{W}{M} = 1 - R_m$$

Substituting these expressions yields:

$$\frac{V + W}{M} = 2 - (R_m S_m Q_m + R_m)$$

and therefore:

$$\mathrm{LFR} = \frac{R_m S_m Q_m + R_m}{2}$$

Final material-level MCI expression (Swiss-adapted)

Material Circularity Indicator adapted to Swiss practice
(Author reformulation following Ellen MacArthur Foundation (2015), using empirically observed Swiss recovery behaviour)

$$\mathrm{MCI}_m = 1 - \left[1 - \frac{R_m S_m Q_m + R_m}{2}\right](1 - U)$$

This expression preserves the structure of the original MCI while embedding **nationally observed recovery, substitution-quality, and value-retention behaviour**. It is used to compute all material-specific MCI values reported in Table 4.2.X.

F.2 Scenario Parameters for R_m, S_m, Q_m, and U
Parameter ranges are derived from the following sources:

- **BAFU (2015, 2018)** - Swiss demolition volumes, recovery rates, and down-cycling pathways
- **Eberhard Unternehmungen (2025)** - high-purity robotic sorting (EbiMIK), early-market performance
- **Röck et al. (2020); Hollberg & Röck (2023)** - European circular-construction case studies

It is emphasised that R_m, S_m, and $Q_m$are **analytical abstractions**, not directly reported statistical variables. They represent **scenario-based operationalisations** of empirical recovery outcomes rather than measured single-point indicators.
Utility factor values

- Components with a 50-year reference life:

$$U = \frac{50}{50} = 1.0$$

- Forever Home structural system (200-year horizon):

$$U = \frac{200}{50} = 4.0$$

F.3 Building-Level MCI Aggregation
The building-level MCI is calculated as a **mass-weighted average** of the material-specific indicators, following Ellen MacArthur Foundation (2015):

$$\mathrm{MCI}_{\text{building}} = \sum_m \alpha_m \ \mathrm{MCI}_m$$

where the mass share $\alpha_m$is given by:

$$\alpha_m = \frac{m_m}{\sum_j m_j}$$

Material masses are taken from Appendix X. Applying this aggregation yields approximate building-level values of:

- **≈ 0.42** - Conventional building
- **≈ 0.63** - High-purity sorting scenario
- **≈ 0.75-0.80** - Forever Home (200-year structure)

F.4 Implementation of the Utility Factor
Building-level formulation (main analysis)
To maintain consistency with the **cradle-to-gate (A1-A3)** system boundary:

- All 50-year components: $U = 1.0$
- Forever Home structural system: $U = 4.0$

Short-lived systems (façades, HVAC, interior timber) are conservatively assigned $U \approx 1.0$.
Component-level formulation (sensitivity analysis)

A sensitivity variant assigns component-specific utility factors following ISO 15686:

$$U_m = \frac{t_{\text{actual},m}}{t_{\text{reference}}}$$

Typical Swiss service-life ranges (SIA 269; ISO 15686):

- Structure: 75-100 years (conventional), 200 years (Forever Home)
- Façade: 30-50 years
- HVAC: 20-25 years
- Interior timber: 15-25 years

Re-aggregation yields building-level MCI values within the same numerical ranges as the simplified model, confirming that the adopted formulation is **methodologically conservative**.

F.5 Cumulative Impact over Multiple Rebuild Cycles

Long-term circularity behaviour is illustrated using a retained-value formulation derived from circular LCA and LCC literature (Pomponi & Moncaster, 2017; Göswein et al., 2021; Hollberg & Röck, 2023):

$$I_{\text{cum}} = \sum_m I_{\text{emb},m} \sum_{i=1}^{n} (1 - R_m S_m Q_m)^{i-1}$$

(Author formulation based on cited sources)

Limiting cases:

- Fully linear system ($R_m S_m Q_m = 0$):

$$I_{\text{cum}} = n \sum_m I_{\text{emb},m}$$

- Near-circular system ($R_m S_m Q_m \to 1$):

$$I_{\text{cum}} \to \sum_m I_{\text{emb},m}$$

F.6 Mass Distribution and Dominance of Structural Concrete

Material mass fractions follow Swiss construction practice (SIA, 2022; Röck et al., 2020):

- Structural concrete: 85-92 %
- Façade systems: 5-8 %
- Interior timber: 2-5 %

Forever Home (central case):

$$\alpha_{\text{conc}} \approx 0.90, \alpha_{\text{façade}} \approx 0.06, \alpha_{\text{timber}} \approx 0.04$$

Because the MCI is mass-weighted, structural concrete dominates the building-level circularity outcome, consistent with findings in **Ellen MacArthur Foundation (2015)** and **Hollberg & Röck (2023)**.

Summary

This appendix provides fully traceable, Word-compatible formulations of all equations used to compute the MCI values in Section 4.2. All steps are explicitly linked to:

- Ellen MacArthur Foundation (2015) - MCI framework
- BAFU (2015, 2018) - Swiss demolition and recovery practice
- Eberhard Unternehmungen (2025) - high-purity sorting pathways
- ISO 15686 - service-life definitions
- Röck et al. (2020); Hollberg & Röck (2023) - circular construction evidence

This ensures methodological consistency and transparency across the circularity, LCA, and economic analyses.

8.7 Appendix G - Circularity Embodied Cost Calculation Basis (with References)

This appendix documents the numerical procedures and parameter conventions used to derive the embodied-cost results reported in **Section 4.3**. The assessment applies a **cradle-to-gate (A1-A3)** system boundary (product stage) and therefore includes only costs attributable to material production and construction-stage delivery, while excluding operational, maintenance, and end-of-life cash flows. This scope follows the logic of building life-cycle costing guidance in **EN 16627 (2015)** and service-life planning principles in **ISO 15686-5 (2017)**, and is consistent with the embodied-impact (A1-A3) boundary used in the environmental and circularity analyses.

G.1 Scope, functional unit, and model purpose

The purpose of the economic model is to isolate the **embodied cost implications** of (i) **material quantities**, (ii) **circularity performance**, and (iii) **service-life assumptions**, under a consistent boundary and transparent replacement-cycle logic. Restricting the analysis to embodied material costs and replacement events avoids speculative assumptions on energy-price evolution, user behaviour, maintenance regimes, and refurbishment strategies, which are not robust at conceptual design stage (EN 16627, 2015; ISO 15686-5, 2017).

All results are expressed per **m² gross floor area (GFA)** to match the mass-based material inventory used in the LCA and MCI models.

G.2 Input data used in Section 4.3

- **G.2.1 Material intensities (mass per m² GFA)**

Material masses m_m are taken from the **geometry-based mass model** developed in **Section 3.5** and used consistently across Chapters 4.1-4.3:

- Reinforced concrete: $m_{\text{conc}} = 1\,200$ (Conventional) / $1\,500$ kg/m² (Forever Home)
- Structural timber (GL/CLT): $m_{\text{timber}} = 50/\,150$ kg/m²
- Aluminium-glass façade system: $m_{\text{façade}} = 45/\,65$ kg/m²

(Section 3.5; Table 4.3.A)

- **G.2.2 Unit-cost proxies (CHF/kg)**

Unit cost proxies c_m are based on **publicly available manufacturer and market sources** and represent **system-level cost proxies** (materials + typical execution requirements reflected in market pricing), not traded commodity prices. The sources used for the unit-cost proxies reported in Table 4.3.A are:

- Concrete: Vigier Beton AG (2025); Holcim Schweiz AG (2025)
- Timber: Binderholz GmbH (2023); Holzkurier (2025)
- Façade systems: Houzy (2024); Jansen AG (2022); Schüco International KG (2022)

These values are applied **consistently across scenarios** to preserve comparability between building concepts.

G.3 Upfront embodied cost per m² (A1-A3)

Formula G.1 - Embodied material cost per material system

(Source: cost aggregation principle consistent with EN 16627 (2015) and ISO 15686-5 (2017), applied here to A1-A3 embodied cost proxies)

$$C_{\text{emb},m} = m_m \cdot c_m$$

where

- $C_{\text{emb},m}$ is the embodied cost of material system m per m² GFA (CHF/m²),
- m_m is mass intensity (kg/m²),
- c_m is the unit cost proxy (CHF/kg).

Formula G.2 - Total upfront embodied cost (A1-A3)

(Source: additive system-cost aggregation; EN 16627, 2015)

$$C_{\text{emb,tot}} = \sum_{m} C_{\text{emb},m}$$

Numerical application (Table 4.3.A):

- Conventional:
  - Concrete: $1\,200 \cdot 0.25 = 300$CHF/m²
  - Timber: $50 \cdot 1.20 = 60$CHF/m²
  - Façade: $45 \cdot 4.00 = 180$CHF/m²
    $\Rightarrow C_{\text{emb,tot}} = 540$CHF/m²
- Forever Home:
  - Concrete: $1\,500 \cdot 0.25 = 375$CHF/m²
  - Timber: $150 \cdot 1.20 = 180$CHF/m²
  - Façade: $65 \cdot 4.00 = 260$CHF/m²
    $\Rightarrow C_{\text{emb,tot}} = 815$CHF/m²

These totals correspond directly to **Table 4.3.A**.

G.4 Replacement-cycle structure (200-year horizon)

Replacement-cycle definitions follow the service-life modelling logic used in **ISO 15686-5 (2017)** and the LCC event-based framing in **EN 16627 (2015)**.

- Conventional / High-Purity scenarios: reference structural cycle $L = 50$years
  Replacement years: $t_i = \{0,50,100,150\}$
  Number of cycles: $n = 4$
- Forever Home: long-life structural cycle $L = 200$years
  Replacement years: $t_i = \{0\}$
  Number of cycles: $n = 1$

(Section 3.3.3; ISO 15686-5, 2017)

G.5 Circularity-adjusted effective cost per cycle

Circularity enters the cost model through the recovery, substitution-quality, and retained-value parameters introduced in **Section 4.2**:

- R_m: recovery rate
- S_m: substitution quality
- Q_m: retained value / value retention

These are operationalised from Swiss demolition practice and high-purity sorting evidence (BAFU, 2015, 2018; Eberhard, 2021) and aligned with circular costing logic discussed in circular LCC literature (Zijlstra, 2023).

Formula G.3 - Material-level effective cost per cycle (circularity-adjusted)

(Source: author formulation consistent with retained-value logic used in the MCI parameterisation (EMF, 2015) and circular LCC modelling (Zijlstra, 2023); parameters $R_m, S_m, Q_m$from Section 4.2)

$$C_{\text{eff},m} = C_{\text{emb},m}\,(1 - R_m S_m Q_m) \;+\; C_{\text{proc},m}\,R_m$$

where

- $C_{\text{eff},m}$is the effective cost contribution of material system $m$per cycle,
- $C_{\text{emb},m}$is the upfront embodied cost term from Formula G.1,
- $(1-R_m S_m Q_m)$is the non-retained fraction of value implied by circularity performance (Section 4.2),
- $C_{\text{proc},m}$is an assumed processing cost associated with recovery (e.g., sorting/reprocessing) applied to the recovered fraction.

Formula G.4 - Building-level effective cost per cycle

(Source: additive aggregation; EN 16627, 2015)

$$C_{\text{eff,tot}} = \sum_{m} C_{\text{eff},m}$$

Processing-cost ranges used in Section 4.3 are treated as scenario parameters (Table 4.3.C) and are sourced as practice-based values for sorting and processing (Eberhard, 2025; Empa, 2021).

G.6 Present-value cumulative cost over 200 years

Present-value calculation follows event-based discounted cash-flow logic consistent with **EN 16627 (2015)**, **ISO 15686-5 (2017)**, and industry guidance for built-asset LCC reporting (RICS, 2016).

Formula G.5 - Discounted cumulative embodied cost over $n$cycles

(Source: discounted cash-flow principle; EN 16627, 2015; ISO 15686-5, 2017; RICS, 2016)

$$C_{\text{cum}} = \sum_{i=1}^{n} \frac{\sum_m C_{\text{eff},m}}{(1+r)^{t_i}}$$

where

- $r$is the real discount rate,
- $t_i$are the replacement years,
- $n$is the number of cycles in the 200-year horizon.

Discount rate assumption:

A real discount rate of $r = 2\%$is adopted, consistent with commonly applied ranges in European building LCC studies and recent review evidence (Cheng et al., 2023), and aligned with the modelling conventions referenced in Section 4.3 (EN 16627, 2015; ISO 15686-5, 2017).

Reported outputs:

Applying Formula G.5 using the scenario cycle structure in Section G.4 and the parameter sets summarised in **Table 4.3.C** yields the present-value costs reported in **Table 4.3.B**:

- Conventional: $\approx 1\,530$CHF/m²
- High-Purity (EbiMIK): $\approx 1\,290$CHF/m²
- Forever Home: ≈ 820CHF/m²

(Section 4.3; Table 4.3.B)

G.7 Simplified building-scale circularity-cost relationship (α-model)

For interpretability at building scale, Section 4.3 introduces a simplified coupling between circularity (MCI) and effective embodied cost per cycle.

Formula G.6 - Simplified building-scale circularity cost proxy

(Source: author simplification for interpretability; circularity concept basis EMF (2015); circular LCC coupling discussion Zijlstra (2023))

$$C_{\text{eff}} = C_{\text{emb}}\,(1 - \alpha \cdot \text{MCI})$$

where

- $C_{\text{emb}}$is the upfront embodied cost of one cycle (Formula G.2),
- MCI is the building-level Material Circularity Index from Section 4.2,
- $\alpha$is a dimensionless scaling coefficient translating circularity change into average retained economic value.

Coefficient selection:

$\alpha \approx 0.6$is used as an empirically calibrated mid-range value, chosen to reflect the magnitude of cost-retention effects implied by the observed shift between the building-level MCI values reported in Section 4.2 (Conventional ≈ 0.42, High-Purity ≈ 0.63, Forever Home ≈ 0.75-0.80) and to remain consistent with the order of magnitude discussed in circular LCC literature (Zijlstra, 2023). This parameter is therefore used as a **transparent approximation**, not a universal constant.

(Section 4.2; Section 4.3; EMF, 2015; Zijlstra, 2023)

G.8 Relative scenario differences

Relative differences are computed using a standard normalisation approach.

Formula G.7 - Relative difference vs. Conventional
(Source: comparative reporting convention consistent with EN 16627 (2015))

$$\Delta = \frac{C_{\text{scenario}} - C_{\text{Conv}}}{C_{\text{Conv}}}$$

This yields the percentage differences reported in the scenario comparison table (Section 4.3).

- **Summary of traceability**

This appendix provides the calculation chain supporting Section 4.3:

1. **Material masses** from the geometry-based model (Section 3.5).
2. **Unit cost proxies** from publicly available manufacturer/market data (Table 4.3.A sources).
3. **Upfront embodied costs** via mass × unit cost (Formulas G.1-G.2).
4. **Cycle structure** from service-life assumptions (ISO 15686-5; Section 3.3.3).
5. **Circularity adjustment** via R_m, S_m, Q_m(Section 4.2; BAFU; Eberhard; EMF; Zijlstra).
6. **Discounted cumulative PV cost** via event-based discounted cash flow (Formula G.5; EN 16627; ISO 15686-5; RICS).
7. **Simplified interpretive coupling** via the α-model (Formula G.6) used to explain economic sensitivity to circularity without overstating precision.