Exploring the Correlation between Building Circularity and Global Warming Potential (GWP)

A Comparative Analysis of Four Building Construction Systems

Scientific work to obtain the degree of Master of Science (M.Sc.)

At the TUM School of Engineering and Design of the Technical University of Munich.

Supervised by Univ.-Prof. Dr.-Ing. Werner Lang

M.Sc. Theilig, Kathrin

Dr.-Ing. Vollmer, Michael

Lehrstuhl für energieeffizientes und nachhaltiges Planen und Bauen

Submitted by Chen Liu

Deisenhofener Str.59

81539, München

Submitted on München, den 19.12.2023

Agreement (Vereinbarung)

zwischen

der Technischen Universität München, vertreten durch ihren Präsidenten,
Arcisstraße 21, 80290 München

hier handelnd der Lehrstuhl für Energieeffizientes und Nachhaltiges Planen und Bauen (Univ.-Prof. Dr.-Ing. W. Lang), Arcisstr. 21, 80333 München

– nachfolgend TUM –

und

Frau Chen Liu

Deisenhofener Str.59, 81539 München

– nachfolgend Autorin/Autor –

Die Autorin / der Autor wünscht, dass die von ihr/ihm an der TUM erstellte Masterarbeit mit dem Titel

Exploring the Correlation between Building Circularity and Global Warming Potential (GWP): A Comparative Analysis of Four Building Construction Systems

☐ auf mediaTUM und der Webseite des Lehrstuhls für Energieeffizientes und Nachhaltiges Planen und Bauen mit dem Namen der Verfasserin / des Verfassers, dem Titel der Arbeit, den Betreuer:innen und dem Erscheinungsjahr genannt werden darf.

■ in Bibliotheken der TUM, einschließlich mediaTUM und die Präsenzbibliothek des Lehrstuhls für Energieeffizientes und Nachhaltiges Planen und Bauen, Studierenden und Besucher:innen zugänglich gemacht und veröffentlicht werden darf. Dies schließt auch Inhalte von Abschlusspräsentationen ein.

☐ mit einem Sperrvermerk versehen und nicht an Dritte weitergegeben wird.

(Zutreffendes bitte ankreuzen)

Zu diesem Zweck überträgt die Autorin / der Autor der TUM zeitlich und örtlich unbefristet das nichtausschließliche Nutzungs- und Veröffentlichungsrecht an der Masterarbeit.

Die Autorin / der Autor versichert, dass sie/er alleinige(r) Inhaber(in) aller Rechte an der Masterarbeit ist und der weltweiten Veröffentlichung keine Rechte Dritter entgegenstehen, bspw. an Abbildungen, beschränkende Absprachen mit Verlagen, Arbeitgebern oder Unterstützern der Masterarbeit. Die Autorin / der Autor stellt die TUM und deren Beschäftigte insofern von Ansprüchen und Forderungen Dritter sowie den damit verbundenen Kosten frei.

Eine elektronische Fassung der Masterarbeit als pdf-Datei hat die Autorin / der Autor dieser Vereinbarung beigefügt. Die TUM ist berechtigt, ggf. notwendig werdende Konvertierungen der Datei in andere Formate vorzunehmen.

Vergütungen werden nicht gewährt.
Eine Verpflichtung der TUM zur Veröffentlichung für eine bestimmte Dauer besteht nicht.

Die Autorin / der Autor hat jederzeit das Recht, die mit dieser Vereinbarung eingeräumten Rechte schriftlich zu widerrufen. Die TUM wird die Veröffentlichung nach dem Widerruf in einer angemessenen Frist und auf etwaige Kosten der Autorin / des Autors rückgängig machen, soweit rechtlich und tatsächlich möglich und zumutbar.

Die TUM haftet nur für vorsätzlich oder grob fahrlässig verursachte Schäden. Im Falle grober Fahrlässigkeit ist die Haftung auf den vorhersehbaren Schaden begrenzt; für mittelbare Schäden, Folgeschäden sowie unbefugte nachträgliche Veränderungen der veröffentlichten Masterarbeit ist die Haftung bei grober Fahrlässigkeit ausgeschlossen.

Die vorstehenden Haftungsbeschränkungen gelten nicht für Verletzungen des Lebens, des Körpers oder der Gesundheit.

Meinungsverschiedenheiten im Zusammenhang mit dieser Vereinbarung bemühen sich die TUM und die Autorin / der Autor einvernehmlich zu klären. Auf diese Vereinbarung findet deutsches Recht unter Ausschluss kollisionsrechtlicher Regelungen Anwendung. Ausschließlicher Gerichtsstand ist München.

München, den	München, den 19.12.2023
	Chen Liu
....	....
(TUM)	(Autor:in)

Declaration (Erklärung)

Ich versichere hiermit, dass ich die von mir eingereichte Abschlussarbeit selbstständig verfasst und keine anderen als die angegebenen Quellen und Hilfsmittel benutzt habe.

München, 18.12.2023, Chen Liu

Ort, Datum, Unterschrift

Acknowledgement

I would like to thank my supervisors, M.Sc. Kathrin Theilig and Dr.-Ing. Michael Vollmer. They infused the paper with inspirational insights and guided me through various challenges with their professional knowledge. Every discussion and collaboration with them profoundly demonstrated their rigorous academic attitude, which has an immeasurable impact on my academic growth.

Additionally, I would like to thank Prof. Dr.-Ing. Werner Lang for his valuable suggestions regarding the content, structure, and framework of the paper, which greatly assisted me in refining my work.

I would also like to thank Dr. Stephan Haug from the Chair of Mathematical Statistics. His expertise in the field of statistics is crucial for the paper.

Finally, I would like to thank my family, especially my boyfriend Hui Liu. During the long days and nights of writing, their unwavering support and understanding saw me through this period.

Table of Contents

Abstract

The construction industry has exerted significant pressure on the ecological environment with the continuous growth of the population. This industry possesses great potential to enhance the material recycling rate, reduce production costs, and achieve a more sustainable sector through reuse and recycling. In response to the goal of reducing carbon emissions, Europa has set an ambitious plan to achieve net zero greenhouse gas (GHG) emissions by 2050. However, studies have shown inconsistencies when considering circularity potential and Global Warming Potential (GWP) separately. Therefore, this study aims to quantitatively analyze the correlation between circularity potential and GWP of the four construction variants (sand-lime brick, brick, wood massive, and wood light) based on the research project ECO+.

Carbon emissions and circularity potential analysis are respectively conducted in Microsoft Excel by calculating GWP and Urban Mining Index (UMI) across the lifecycle. This study utilizes a modified Life Cycle Assessment (LCA) modeling method based on existing recycling modeling approaches, adjusting data from the Ökobaudat database according to the future recycling potential of materials. The assessment of circularity potential is achieved through the UMI, developed by the University of Wuppertal, which quantifies the proportion of recycled materials in the total mass of all materials used over their life cycle. Distinguishing different quality levels of recycled material use in the pre-use and post-use phases is an essential step for the circularity assessment. After obtaining the results of GWP and UMI, their correlation is visually analyzed through scatter plots and combo diagrams at the building, component, and material levels and quantified by calculating the correlation coefficient.

The results indicate a certain negative correlation between GWP and UMI. The Wood construction variants perform better than the brick construction variants regarding GWP and UMI. This paper enhances the researchers' understanding of the impact of various building construction variants choices within the research project ECO+ and provides valuable insights on the correlation between carbon footprint and circularity potential.

Kurzfassung

Die Bauindustrie hat mit dem kontinuierlichen Wachstum der Bevölkerung erheblichen Druck auf die ökologische Umwelt ausgeübt. Durch Wiederverwendung und Recycling besitzt diese Branche großes Potenzial, um Recyclingfähigkeit der Baumaterialien zu erhöhen, Produktionskosten zu senken und einen nachhaltigeren Sektor zu erreichen. Als Reaktion auf das Ziel, die Kohlenstoffemissionen zu reduzieren, hat Europa einen ehrgeizigen Plan aufgestellt, um bis 2050 netto null Treibhausgasemissionen zu erreichen. Studien haben jedoch Inkonsistenzen aufgezeigt, wenn Recyclingfähigkeit und Globales Erwärmungspotenzial (GWP) separat betrachtet werden. Daher zielt diese Studie darauf ab, die Korrelation zwischen Recyclingfähigkeit und GWP der vier Baukonstruktionsvarianten (Kalksandstein, Ziegel, Massivholz und Leichtholz) basierend auf dem Forschungsprojekt ECO+ quantitativ zu analysieren.

Die Analyse von Kohlenstoffemissionen und Recyclingfähigkeit wird jeweils in Microsoft Excel durchgeführt, indem GWP und der Urban Mining Index (UMI) über den gesamten Lebenszyklus berechnet werden. Diese Studie verwendet eine modifizierte Methode der Recyclingmodellierung, die auf bestehenden Recyclingmodellierungsmethoden basiert, wobei die Daten aus der Ökobaudat-Datenbank entsprechend des zukünftigen Recyclingpotenzials der Baumaterialien angepasst werden. Die Bewertung des Kreislaufpotenzials wird durch den UMI erreicht, entwickelt von der Universität Wuppertal, der den Anteil der recycelten Materialien an der Gesamtmasse aller Materialien über ihren Lebenszyklus quantifiziert. Dabei ist die Unterscheidung verschiedener Qualitätsstufen der zirkulären Materialnutzung vor und nach der geplanten Nutzung ein wesentlicher Schritt. Nach Erhalt der Ergebnisse von GWP und UMI wird ihre Korrelation sowohl durch Streudiagramme als auch durch Kombinationsdiagramme auf der Ebene von Gebäude, Bauteile und Materialien visuell analysiert und durch Berechnung des Korrelationskoeffizienten quantifiziert.

Die Ergebnisse deuten auf eine gewisse negative Korrelation zwischen GWP und UMI hin. Die Holzbauvarianten schneiden hinsichtlich GWP und UMI besser ab als die Ziegelbauvarianten. Dieses Papier verbessert das Verständnis der Forscher über die Auswirkungen der Auswahl verschiedener Baukonstruktionsvarianten innerhalb des Forschungsprojekts ECO+ und bietet wertvolle Einblicke in die Korrelation zwischen Kohlenstoff Fußabdruck und Kreislaufpotential.

List of Abbreviations

AP	Acidification potential
BBSR	Bundesinstitut für Bau-, Stadt- und Raumforschung
	Federal institute for research on buildings, urban affairs and spatial development
BIM	Building information modeling
BNB	Bewertungssystem Nachhaltiges Bauen
	Assessment system for sustainable building
CC	Conventional concrete
CDW	Construction and demolition waste
CE	Circular economy
CEAP	Circular economy action plan
CLP	Closed-loop potential
CRD	Construction, renovation, and demolition waste
EMF	Ellen MacArthur Foundation
EoL	End of Life
EPD	Environmental product declaration
EU	European Union
GHG	Greenhouse gas
GWP	Global warming potential
IEA	International energy agency

ISO	The international organization for standardization
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LP	Loop potential
MCI	Material circularity indicator
MLP	Material-Loop-Potential
MRC	Material-Recycling-Content
OECD	Organization for Economic Co-operation and Development
PENRT	Total non-renewable primary energy
RC	Recycled concrete
UMI	Urban mining index
UNEP	United nations environment programmer
NGF	Net ground floor

Glossary

Closed-loop potential (CLP): materials whose quality level can be maintained in closed cycles (reutilization and recycling).

Embodied carbon: greenhouse gas emissions arising from the manufacturing, transportation, installation, maintenance, and disposal of building materials.

Global warming potential (GWP): measure of the relative radiative effect of a given substance compared to another, integrated over a chosen time horizon.

Greenhouse gas (GHG): gas that contributes to the greenhouse effect by absorbing infrared radiation in the atmosphere.

Life cycle assessment (LCA): compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle.

Life cycle interpretation: phase of life cycle assessment in which the findings of either the inventory analysis or the impact assessment, or both, are evaluated in relation to the defined goal and scope in order to reach conclusions and recommendations.

Life cycle inventory analysis (LCI): phase of life cycle assessment involving the compilation and quantification of inputs and outputs for a product throughout its life cycle.

Life cycle impact assessment (LCIA): phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product.

Loop potential (LP): materials whose quality diminishes in open cycles (further use and downcycling).

Material loop potential (MLP): potential future proportion of recycled materials in a product, given maximum optimization of production in terms of its secondary raw material.

Material recycling content (MRC): proportion of recycled materials and/or renewable raw materials in the composition of materials.

Operational carbon: greenhouse gas emissions produced over the lifetime use of the building.

P-value: a measure of how likely or probable it is that any observed correlation is due to chance.

Spearman rank correlation coefficient (ρ): a nonparametric measurement correlation used to determine the relation existing between two sets of data.

Urban mining index: the circular material's share in the entirety of materials used in a building's life cycle.

1. Introduction

1.1. Background

With the continuous growth of the population, the development of the construction industry has brought significant challenges to the extraction of resources, energy consumption, waste disposal, carbon emissions, and climate change. The sector is a major consumer, accounting for about 50% of all extracted materials (EMF, undated), and is responsible for approximately 100 billion tons of waste from construction, renovation, and demolition annually (CRD), predominantly disposed of in landfills, leading to environmental concerns such as leachate and H_2S gas emissions (Chen et al., 2022). According to the Organization for Economic Co-operation and Development (OECD, 2019), in a linear economy, the global extraction of raw materials will double by 2060, accelerating the depletion of existing resources.

The circular economy (CE) is an approach that aims to transform the traditional take-make-waste systems into a regenerative model by rethinking how we manage resources to abate waste and pollution (EMF, 2013). As a new way of thinking, CE turns the traditional linear model into a cycle that can potentially foster sustainable development by reducing the acquisition of raw materials and the generation of waste (Zhang et al., 2022). In alignment with these principles, the European Commission (2020) adopted the new circular economy action plan (CEAP) to expedite the European Union's (EU) progression towards a CE. The CE model has gained significant attention in recent years and is considered as a crucial factor for achieving sustainable urban development (Diemer & Dierickx, 2020).

Several design support tools and indicators have emerged to foster circularity within the construction industry. Nevertheless, considering the variability of national regulations, the complexity of building designs, and the interconnectedness among various building components, a universally recognized framework for circularity assessment is still lacking (Parchomenko et al., 2019; Gillott et al., 2023; Al-Obaidy et al., 2022). Moreover, due to the absence of relevant regulations and the certifications of secondary-use materials, the use of recycled and reused materials is still challenging, resulting in materials with significant recycling potential being wasted (Al-Obaidy et al., 2022; Mrad & Frölén Ribeiro, 2022).

Globally, the building sectors are responsible directly and indirectly for about 37% of global energy- and process-related CO_2 emissions, with 8% from fossil fuel used within buildings, 19% from electricity and heat generation for buildings operations, 6% for manufacturing construction materials such as cement, steel, and aluminum and around 2-4% from other building materials including bricks and glass (IEA, 2022f). According to UNEP (2022), the year 2021 witnessed a historic peak in CO_2 emissions due to the post-pandemic economic resurgence, with buildings operations associated with the construction sector reaching approximately 10 $GtCO_2$, while production of building materials contributed 3.6 $GtCO_2$. By 2050, half of the CO_2 emissions from the construction industry will originate from new buildings, compared to the current figure of only 28% (Sánchez-Garrido et al., 2022). In line with the European Green Deal, Europe aspires to become the first climate-neutral continent, with goals of a minimum 55% reduction in net greenhouse gas (GHG) emissions by 2030 compared to 1990 and no net GHG emissions by 2050. Despite these aspirations, UNEP's 2022 report highlights that the construction and building sector has not yet to align with the pathway required to achieve carbon neutrality by the midcentury. The building sector requires further adjustments and interventions.

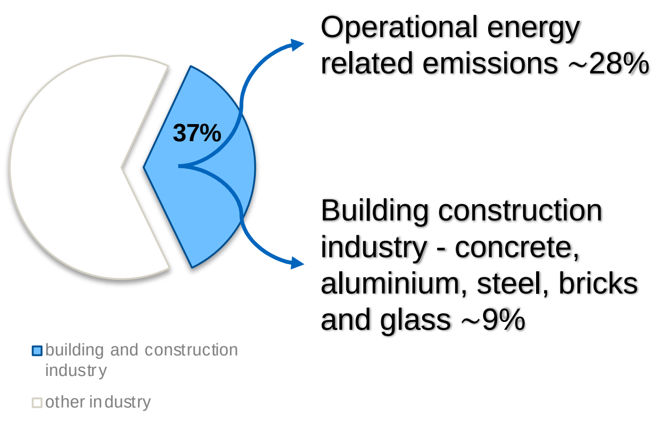


Figure 1-1: Share of building and construction industry in global energy and process emissions in 2021 (IEA, 2022)

According to the Danish national strategy for sustainable construction, a key element is adopting LCA and its integration into national building codes as a requirement for all buildings (UNEP, 2022). LCA emerges as a powerful method that assists designers and engineers in designing and evaluating the sustainability of buildings by analyzing the entire lifecycle, spanning from raw material extraction to End-of-Life (EoL) (Mondello & Salomone, 2020). Furthermore, it is imperative to assess GHG emissions using indicators such as GWP, which quantifies the contributions of various gases, including CO_2, methane, and nitrous oxide, on global warming (Biron, 2016).

1.2. Aim of the Research

Despite the substantial impact of embodied carbon on global GHG emissions, it has previously received insufficient attention in building emission reduction strategies (UNEP, 2022). Most current building codes and regulations focus primarily on operational carbon emissions (UNEP, 2022). However, addressing embodied emissions is as crucial as operational carbon to achieve net-zero carbon. Previous studies have shown that the results could be the opposite when considering circularity performance and GWP separately (Rigamonti & Mancini, 2021; Poolsawad et al., 2023). Considering both building circularity performance and GWP targets is crucial for engineers to make informed design decisions, highlighting the need to explore the correlation between these metrics. To this end, this paper is dedicated to examining and evaluating the building circularity and GWP of four construction variants proposed by the research team. The objective is to identify the most optimal building construction solution that minimizes embodied carbon emissions and maximizes circularity performance. Consequently, this paper aims to delve into the correlation between building circularity and GWP through statistical analysis within the framework of the research project ECO+, providing valuable insights to promote more sustainable decisions within the context of CE.

1.2.1. Research Questions

This paper seeks to answer two primary research questions:

1. Among the four building construction variants proposed by the research team of the research project ECO+, which should be selected when evaluating building circularity performance and LCA independently?

2. What is the relationship between building circularity performance and GWP values, and how are these metrics correlated?

1.2.2. Structure of the Paper

This paper first gives a brief overview of background, highlighting the necessity and associated challenges of implementing CE and LCA, in the context of several global environmental issues posed by the construction industry. It also introduces the research objectives and research questions.

Chapter 2 reviews the current state of building circularity performance analysis and LCA, along with the main tools and indicators currently utilized. It also identifies existing research gaps and limitations.

Chapter 3 provides a detailed description of the methods used in the research, specifically focusing on determining GWP through LCA and analyzing building circularity performance by calculating the UMI. Additionally, the chapter presents the statistical analysis methods used to explore the correlation between GWP and UMI.

Chapter 4 focus on presenting the calculation results, with the key indicators of GWP, UMI, and their correlation.

Chapter 5 discusses the main findings and limitations of the research, considering their implications for the further development of the research project ECO+ within the context of the CE.

Finally, Chapter 6 concludes the paper by summarizing the essential findings and providing directions for the future research.

2. State of the Art

2.1. Building Circularity in the Context of Circular Economy

2.1.1. Definition of the Circular Economy

The theory and practice of the CE have attracted widespread academic attention and are experiencing a growing trend (Munaro et al., 2020). Since that the concept of CE originates from the convergence of ideas from multiple scientific disciplines and its scientific and research foundations are still in their early stages (Korhonen et al., 2018), there is still no consensus on the definition of the CE (Mrad & Ribeiro, 2022).

The EMF, which has a significant impact on driving the development of the CE, identifies two modes of material cycling of CE through the butterfly diagram: the technical cycle, where products and materials are maintained in use through reuse, repair, remanufacturing, and recycling, and the biological cycle, where nutrients in biodegradable materials are returned to nature for regeneration (EMF, 2019). These two modes align with the three core principles of the design-driven CE system proposed by EMF:

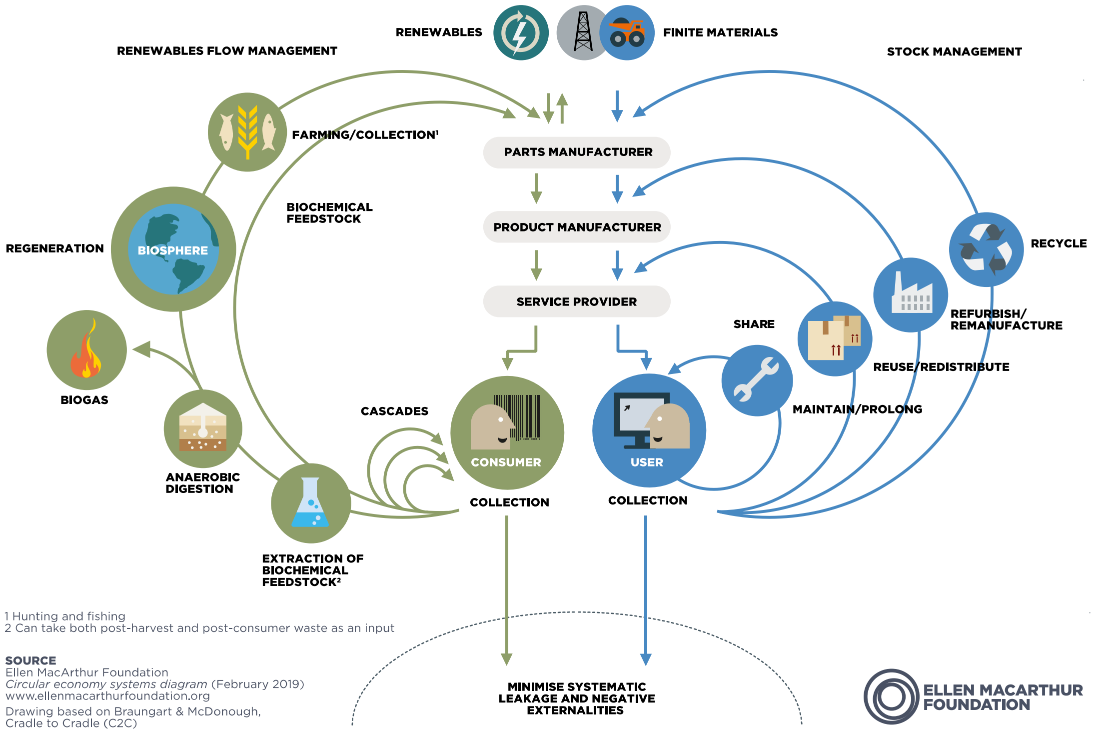


Figure 2-1: The butterfly diagram: visualizing the CE (EMF, 2019)

“eliminating waste and pollution,” “circulating products and materials (at their highest value),” and “regenerating nature,” to benefit both humanity and the natural environment.

As a highly cited literature, Kirchherr et al. (2017) propose the following definition of CE after reviewing the 114 existing definitions at that time: “A CE describes an economic system that is based on business models which replace the ‘end-of-life’ concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes, thus operating at the micro level (products, companies, consumers), meso level (eco-industrial parks) and macro level (city, region, nation and beyond), to accomplish sustainable development, which implies creating environmental quality, economic prosperity, and social equity, to the benefit of current and future generations.” This definition emphasizes two key elements: the operation of the CE across different dimensions and its goal of achieving sustainable development in multiple dimensions (Ekins et al., 2019).

Potting et al. (2017) developed a framework of circularity strategies within the CE production chain that include the 10R principles (Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, Recover). They established a prioritization order based on the degree of circularity: prioritizing smarter product use and manufacture, followed by extending product lifespan, and incineration of materials with energy recovery has the lowest priority. This prioritization is based on the consideration that a higher degree of material circulation and a longer retention time in the product chain generally lead to a reduced need for natural resources in manufacturing new products (Potting et al., 2017). Morseletto (2020) argues that although this categorization provides inspiration for studying CE, it may not be applicable to certain products and conditions.

Geissdoerfer et al. (2017) defined the CE as “a regenerative system in which resource input and waste, emission, and energy leakage are minimized by slowing, closing, and narrowing material and energy loops. This can be achieved through long-lasting design, maintenance, repair, reuse, remanufacturing, refurbishing, and recycling.”

Due to the involvement of diverse stakeholders and the dynamic nature of the CE, it is not feasible to have a singular universal definition of CE (Korhonen et al., 2018). Despite the variations in definitions, the core elements of CE remain consistent, focusing on a closed-loop system that integrates environmental sustainability, resource efficiency, and economic benefits, as emphasized by Lieder and Rashid (2016).

2.1.2. Circular Economy in the Building Sector

The linear economic model long practiced by the construction industry has made it a high consumer of energy and resources while generating large amounts of waste and GHG emissions (Mrad & Ribeiro, 2022). The EU alone produces more than 800 million tons of construction and demolition waste (CDW) annually, accounting for more than one-third of all waste generated in the EU (European Commission, 2017). In most countries, CRD waste is predominantly disposed of by landfills or incineration (Chen et al., 2022), leading to a tiny fraction of construction materials' economic value and durability being utilized (Eberhardt et al., 2019). However, with the projected addition of 3 billion middle-class consumers by 2030, the balance of supply and demand for limited resources is being challenged, necessitating a transformation of the "take-make-dispose" economic model, which relies on cheap and accessible resources (EMF, 2014).

In such a context, the new paradigm of a CE that changes the current linear economic model attracts attention, particularly relevant for the building sector. The building sector is considered one of the three auspicious sectors for implementing the CE strategy (SYSTEMIQ & EMF, 2017), which has a great potential to create a highly resource-efficient, low production cost, and more sustainable construction sector through reuse and recycling (E. Eberhardt et al.,2019; Diemer & Dierickx, 2020; Norouzi et al., 2021).

Academic interest in this area is growing, as evidenced by Norouzi et al. (2021), who collected and analyzed 7000 publications in Web of Science and Scopus from 2005 to 2020. As shown in Figure 2-2, the CE-related literature in the building sector has grown at an average annual rate of 18.5% since 2008, reaching a total of 1112 articles in 2020, indicating that the field has received a high level of interest and will continue to attract more research (Norouzi et al., 2021). In academic literature, research focuses on the following topics, which are prominent in the field: building energy and resources, recycling of construction materials, waste management, environmental impact, green buildings, and economic benefits (Ghisellini et al., 2016; Norouzi et al., 2021). According to a review by Mrad & Ribeiro (2022) of the top 1750 publications from Scopus and Web of Science, the majority of studies focused on promoting the concept of the CE through building materials, with some studies emphasizing recycling and reuse, and a minority of research shifted their focus towards seeking new design approaches and legislation. Haas et al. (2015) argues that the promotion of CE should prioritize shifting from fossil fuels to renewable energy sources and reduce overall resource consumption rather than relying solely on recycling and reuse since recycling may not always lead to reduced material consumption.

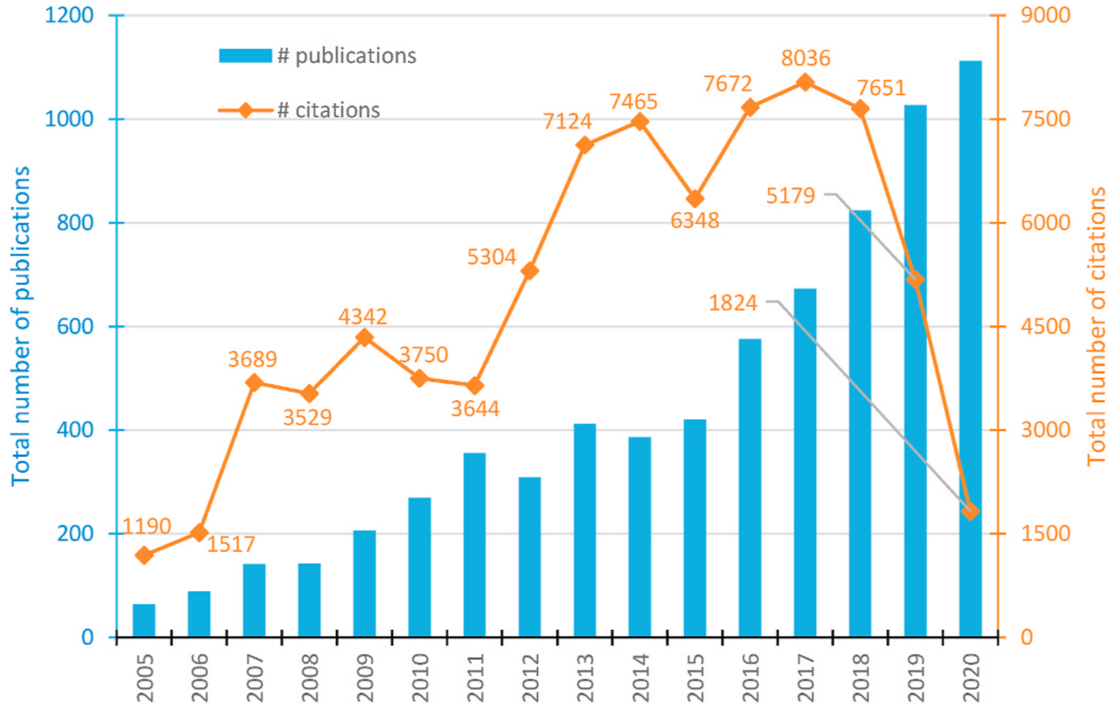


Figure 2-2: Trends in publication volume and total citation of CE in the building sector (2005-2020) (Norouzi et al., 2021)

However, the global implementation of CE in the construction industry is currently in the early stages of development, both at the theoretical and practical levels, and needs a more comprehensive and standardized framework (Ghisellini et al., 2016; Munaro et al., 2020). Eberhardt et al. (2019) found that although reuse offers higher economic and environmental benefits, recycling and energy recovery remain the most common CE practices in the construction industry. Adams et al. (2017) emphasize the need to expand the CE application throughout the entire supply chain beyond the limited focus on waste reduction and recycling of construction debris at the EoL stage, with CE indicators, tools, and government incentives playing a crucial role. Minunno et al. (2018) found that the application of the CE framework in the construction industry is mainly limited to the use of by-products in concrete production and the application of recycled concrete. Bilal et al. (2020) assessed the implementation of CE in the construction industry in developing countries using a CE evaluation scale based on seven dimensions and 24 indicators. Their findings indicated that the overall level of CE implementation in the construction sector could be more satisfactory, with the best performance in energy and the worst outcomes in waste disposal. Though analyzing the circular performance of 89 building products, Dräger et al. (2022) found that the application of CE in the German construction industry is still in its early stages, with significant room for improvement in the recyclability of construction products.

The recycling utilization of building materials varies considerably. Poolsawad et al. (2023) conducted an analysis using the material circularity indicator (MCI) for various construction materials. They found that construction steel is almost 100% recyclable, while mortar and cement have low recycling performance, with the majority being disposed of in landfills post-use. Wood can have a high recycling potential but is highly related to its physical properties, production technology, and use process (Poolsawad et al., 2023; Diaz-Balteiro et al., 2022). Moreover, research has shown that optimizing material selection combinations, such as wood, steel, and glass, can significantly facilitate easier disassembly at the EoL stage, enabling effective recycling or reuse (Eberhardt et al., 2019).

Hart et al. (2019) identified four primary categories of barriers hindering the development of the CE: cultural, regulatory, financial, and sector-specific barriers. Kanters (2020) highlighted additional challenges, explicitly pointing to the conservative nature of the construction industry, lack of political prioritization, and dependence on the entire construction sector. On the other hand, Minunno et al. (2018) suggest that the barriers to applying CE in traditional buildings are related to their holistic nature, the absence of standardized measures, and the underdeveloped closed-loop supply chains. These differing perspectives highlight the complexity and multifaceted nature of more broadly applied CE practices in the construction industry.

2.1.3. Existing Building Circularity Indicators and Tools

For the construction industry to achieve CE and enhance profitability, it is essential to plan and integrate circular business models from the design phase (Biccari et al., 2019). This viewpoint emphasizes the pivotal role of designers in considering the post-use recycling of building materials during the early design phase. Methods and tools for measuring the implementation level of CE provide valuable insights for designers and benefit all stakeholders, further advancing CE development (Núñez-Cacho et al., 2018). However, Khadiam et al. (2022) note that at the current stage, most indicators primarily focus on material circulation, with limited research addressing the dismantlability, adaptability, and reusability of structures. The varied development of CE currently across different spatial levels, including micro, meso, and macro levels, leads to a lack of recognized standardized and comprehensive measurement indicators and methods for CE, which hinders the implementation of CE (Pascale et al., 2021; Smol et al., 2017).

Circularity tools and indicators contribute to designing of new products and systems and benchmark the circularity level among different companies, making them valuable for circular decision-making (Rigamonti & Mancini, 2021). “The Circular Design Guide” by the EMF and IDEO aims to help designers create practical, sustainable thinking by providing general CE strategies and principles. Parchomenko et al. (2019) collected and evaluated 63 current CE metrics, finding that the most of these indicators primarily focus on the material level, lacking consideration for the product-system dynamic and value maintenance. Innovative tools like the One Click LCA software quantify the circularity of materials in the building lifecycle as a percentage by calculating the average of materials recovered and returned, providing the designers with a visual representation of the material circularity in the building lifecycle. Rosen (2021) developed a tool for systematically documenting building structures to calculate and evaluate the building circularity potential, quantifying building circularity potential through the UMI. Biccari et al. (2019) proposed a framework that utilizes building information modeling (BIM) to collect inputs and visualize circularity indicators as attributes in 3D models for improving design solutions based on circularity levels and overall life cycle costs. The MCI, developed by EMF and Granta Design, measures the extent of material recovery in products, helping companies assess the circularity performance of their products.

However, these measurement tools have different limitations. Firstly, the indicators vary significantly in form and content, making it challenging to select a more suitable one among numerous indicators for specific projects. Secondly, as noted by Rigamonti and Mancini (2021), these circularity indicators do not directly reflect the sustainability of a product or system.

2.2. Recent Development of Life Cycle Assessment

2.2.1. Recent Development and Challenges of Life Cycle Assessment

Since the beginning of the 21st century, LCA has gained increasing attention among practitioners, politicians, and stakeholders, and LCA thinking has been increasingly reflected in European policies (Buyle et al., 2013). Anand and Amor (2017) noted a significant growth in building LCA publications, which more than doubled between 2011 and 2015. LCA is a recognized scientific method for assessing and quantifying the potential environmental impacts of a product throughout its entire lifecycle, standardized by The International Organization for Standardization (ISO) in ISO 14040 (Rigamonti & Mancini, 2021). LCA was initially applied to products in other industries and only started in the construction sector in 1990, gradually reaching the most advanced level (Cabeza et al., 2014). Due to factors such as high uncertainty in the construction process and lower levels of standardization compared to industrial processes, the application of LCA in the construction field has posed challenges (Buyel et al., 2013). Lotteau et al. (2015) argue that most LCAs primarily focus on life cycle energy assessments, emphasizing energy-related issues rather than addressing broader environmental impacts. Anand and Amor (2017) reviewed the application of LCA in the construction industry and identified the challenges faced at different stages of LCA implementation (Table 2-1). For LCA to become a reliable assessment tool for addressing environmental issues in the building sector, further improvements are needed to address unresolved issues (Anand & Amor, 2017).

Table 2-1: Summary of challenges in the field of LCA of buildings (Anand & Amor, 2017)

Focus Area	**Challenges**
Functional unit	1. Use of varied functional units causing comparison restrictions 2. Difference in calculated and actual impacts 3. Reliability of calculated service life of a building
System boundaries	1. Not much data on refurbishment analysis of existing buildings 2. Lack of a procedure for choosing relevant system boundaries
Inventory analysis	1. Uncertainty in data collection methods

	2. Missing data
Impact assessment	1. Overall reduction of impact from use of buildings for example from a city 2. Making embodied energy an impact indicator 3. Comparison of building LCA results 4. Addressing the implementation of dynamic LCA in industry and also the evaluation of suggested alternatives as a result of dynamic LCA 5. Difference in predicted and actual impacts
Beyond LCA	1. Increase the use of LCA in industry 2. Varied results from LCA integrated certifications & LCA 3. Improve availability of product data 4. Impacts based on deconstruction before the assumed life time

2.2.2. Existing Life Cycle Assessment Tools

Anand and Amor (2017) highlight that despite the extensive research on LCA, it has not yet been widely used by practitioners in the construction industry. They propose that integrating LCA into construction tools is considered the most effective way to introduce LCA into the market. Various LCA software tools have emerged for assessing specific products or buildings (Anand & Amor, 2017). Among them, two prominent software tools are SimaPro, developed by Pre-sustainability, and GaBi, developed by PE International, which offers comprehensive impact category assessments (Herrmann & Moltesen, 2015). A study by Herrmann and Moltesen (2015) showed that the LCA results obtained using these two software tools are generally similar in most cases, though differences exist in the impact assessment implementation due to variations in their respective databases. Cabeza et al. (2014) classified these two software tools as Level-1, primarily used for product comparison. LCA tools such as Athena Ecocalculator and Envest 2 belong to Level-2, which are whole-building decision support tools. They consider the impact of a change in one building material on generating other related materials (Cabeza et al., 2014). Additionally, the online tool eLCA is developed by the Federal Institute for Research on Buildings, Urban Affairs and Spatial Development (BBSR), which allows for quantitative assessment of buildings based on the Ökobaudat database published by BBSR. The Ökobaudat database, based on the underlying GaBi database, undergoes rigorous quality screening to meet the requirements of EN15804 and Assessment System for Sustainable Building (BNB).

2.2.3. Global Warming Potential of different Construction Materials

Whether in other fields or in the construction domain, GHG emissions are one of the most commonly used indicators in LCA publications (Anand & Amor, 2017). The construction industry consumes over half of the world's total steel production (Moynihan & Allwood, 2012) and more than 14 billion m^3 of concrete annually (Global Cement and Concrete Association, 2023). However, the two most common building materials are also prominent contributors to global CO_2 emissions (Kerr et al.,2022; Holappa, 2020; Zhu, 2011).

Gong et al. (2012) conducted a LCA on three different frame structures in Beijing: concrete, light steel, and timber. They found that the net CO_2 emissions of the concrete frame structure were 44% higher than those of the light steel frame and 49% higher than those of the timber frame. Miller et al. (2016) discovered that for high-compressive strength concrete, using concrete containing replacement binder gives a lower GWP, while for low-strength concrete, using only cement as the binder results in lower GWP values compared to mixtures with a high content of replacement binders. Evangelista and Brito (2007) reported that concrete made with fine recycled concrete aggregates instead of fine natural aggregates has a lower GWP value. Knoeri et al. (2013) indicated that the GWP of recycled concrete (RC) is comparable to that of conventional concrete (CC) if the amount of additional cement and the additional transport used for RC is limited. Kerr et al. (2022) found that using dimensional structural stone instead of concrete and steel significantly reduced global carbon emissions.

Compared to other building materials, professionals consider wood products less of a burden on the environment and the most environmentally friendly materials for building design (Li & Xie, 2013). A study of the environmental utility of six building cases shows that replacing primary structural materials with wood can reduce GWP by an average of 60% (Milaj et al., 2017).

2.3. Relationship between Circularity and Global Warming Potential

CE and LCA share a common goal of reducing environmental burdens, making LCA suitable for assessing the environmental benefits of circular product design or the extent of CE development (Haupt & Zschokko, 2017). Peña et al. (2021) also recognize that LCA is a highly suitable tool for evaluating and enhancing the sustainability of CE strategies. However, Rigamonti and Mancini (2021) point out that LCA may not effectively measure the level of circularity in a system, partly because it typically analyzes products within the framework of a linear economy, which encompasses the life cycle from the cradle to grave.

Poolsawad et al. (2023) argue that there is a negative correlation between building circularity performance and GWP, suggesting that improving building circularity performance simultaneously leads to a reduction in GHG emissions. Tavares et al. (2021) found that prefabrication can significantly reduce construction waste generation and increase the recycling rate of building materials, making it advantageous in the transition toward a CE. Similarly, Mo et al. (2023) demonstrated that through their study of a highly prefabricated office building with an assembly rate of up to 96.8%, its carbon emissions are 22 [kg CO_2-eq./m^2] lower than non-prefabricated construction methods, highlighting the effective reduction of carbon emissions achieved through prefabrication.

However, some recent studies of CE projects have shown that the results could also be contradictory when considering building circularity performance and LCA separately (Rigamonti & Mancini, 2021; Poolsawad et al., 2023). Most of these studies focused on sectors like food packaging, batteries, and tires, which may not be directly applicable to highly complex construction fields. CE concept implies that a building with high recycling performance should return its materials to the product cycle at the end of its useful life. However, the carbon emissions associated with the demolition, transportation, and disposal processes must be considered. Haupt and Zschokke (2017) emphasize that the most circular choice is not necessarily the most environmentally favorable, partly because the current LCA is still based on the current energy structure and material management. This situation could change if the energy structure becomes fully renewable.

Rigamonti and Mancini (2021) suggest that to accurately assess the overall environmental performance of a product or system, it is necessary to conduct a LCA analysis initially and then continue with circularity analysis after eliminating some unfavorable options to advance the decision-making process, thus helping to maximize environmental performance. They also call for the scientific community to define a scientific and transparent standardized process to further promote the development of CE. In the construction domain, more research on the relationship between circularity and GWP still needs to be done (Brändström & Saidani, 2022).

2.4. Existing Gaps of Building Circularity Performance and Life Cycle Assessment

The Literature on building circularity performance and LCA analysis identifies several existing gaps that need addressing:

1. **Lack of In-Depth Research on CE Indicators and Methods**: There is a noted absence of detailed research on indicators and methods for assessing CE at the product, company, and regional levels (Haas, 2015; Elia et al., 2017; Dräger et al., 2022).

2. **Alignment of CE Strategies with Sustainable Development**: As CE strategies are not always inherently aligned with the concept of sustainable development, it is necessary to conduct quantitative evaluations and comparisons of circularity indicators and environmental performance indicators, such as GWP (Brändström & Saidani, 2022; Rigamonti & Mancini, 2021).

3. **Consensus on CE in the Construction Industry globally**: There is a lack of widespread consensus on CE throughout the construction industry, and there is limited research from a systems perspective to transform business models and promote design for disassembly and reuse at the EoL stage of a product (Adams et al., 2017).

4. **Integrated Approach for Construction Stakeholders**: There is a need for more research to support an integrated approach that enables construction stakeholders to track materials and assess their quality, which can help reduce waste during the design phase (Mrad & Ribeiro, 2022).

5. **Evaluation of Residual Pollutants in Material Flows**: The separation and exclusion of pollutants entering the material cycle during the use, production, and collection stages is a critical issue in the context of CE， and there is a lack of research evaluating residual pollutants in material flows during the recycling process (Haupt & Zschokke, 2017).

6. **Influence of Different Building Lifespan on LCA Results**: Most papers consider the lifespan when conducting LCA, but generally, the lifespan is assumed, leading to potential errors in the analysis (Anand & Amor, 2017). More research is needed to consider the impact of variant building lifespan on LCA results (Cabeza et al., 2014).

7. **Effectiveness of LCA in Measuring Circularity**: The current application of LCA may not adequately capture the circularity of a system. This limitation partly from its focus on analyzing products within the current energy structure and a linear economic framework that spans a cradle-to-grave lifecycle. (Rigamonti & Mancini, 2021; Haupt & Zschokke, 2017)

8. **Link between Environmental Impacts and Economic Costs**: More research is needed to establish the connection between environmental impacts and economic costs, as the economic costs of mitigating or avoiding these impacts are rarely reflected in the prices of the resulting products (Buyle et al., 2013).

This article aims to contribute to the second and the seventh gap in existing literature based on the research project ECO+.

3. Methodology

3.1. Analytical Approach

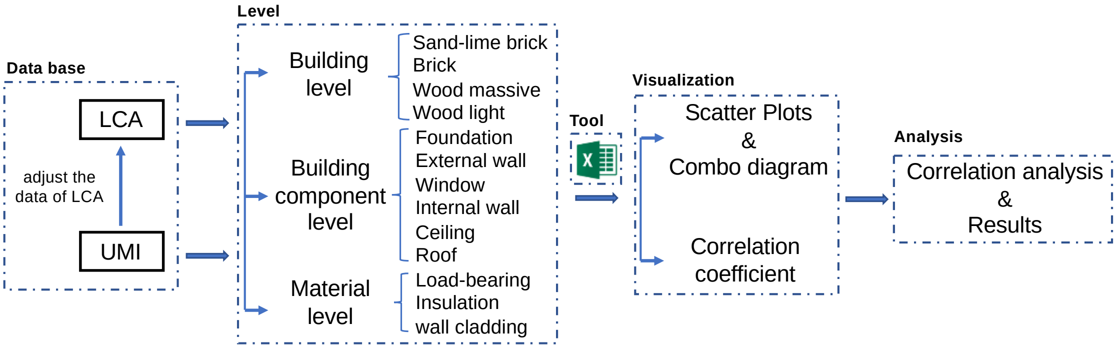


Figure 3-1: Workflow of evaluating correlation between UMI and GWP based on four building construction variants for research project ECO+

Figure 3-1 illustrates the analytical process of investigating the correlation between building circularity performance and GWP based on four variations of building constructions from the research project ECO+: sand-lime brick, brick, wood massive, and wood light. The essential data for the correlation analysis is derived from the UMI and GWP analyses conducted on these four building construction variants.

The circularity performance analysis is conducted by calculating the UMI in Microsoft Excel based on the mass of the materials within the lifecycle of the building. A detailed circularity potential analysis in the pre-use and post-use phase is applied to the materials in each building component. In the pre-use phase, the circularity potential of the materials is calculated based on the Material-Recycling-Content (MRC) sourced from Atlas Recycling. UMI conducts high-grade and low-grade EoL scenarios for materials in the post-use phase to assess their future recycling potential. Achieving a high-grade EoL scenario depends on evaluations at both the structural level (i.e., the dismantlability of building components and the feasibility of obtaining individual parts) and the economic level (i.e., the value of materials and the costs associated with dismantling).

The LCA follows the requirements of ISO 14040 and ISO 14044, based on integrated material inventories and the Ökobaudat database. While the Ökobaudat database typically provides a singular simulation for the EoL stage of materials, the LCA analysis in this context is further refined to integrate the recycling rate of the building materials. This enhancement is achieved by integrating the future recycling rate of the materials obtained from the UMI analysis into the LCA analysis to adjust the LCA data of the C3-C4 stages. All obtained data will be inputted into Excel for calculations, comparisons, and further processing to obtain the total GWP values for each building's construction variant.

This study conducts an in-depth analysis of the correlation between UMI and GWP at three levels: the building level, the building component level, and the material level.

- **Building Level Analysis**: At this level, a comparison is made between the total GWP values in [kg CO_2-eq./m^2-NGF] and the total recycling potential in [%] of buildings across the four building construction variants.

- **Building Component Level Analysis**: At the building component level, a comparison is made for each major building component, including foundation, exterior wall, window, interior wall, ceiling, and roof, examining their total GWP values in [kg CO_2-eq./m^2-building component] and recycling potential in [%] under the four building construction variants.

- **Material Level Analysis**: At this level, the study categorizes building materials within the research project ECO+ by function and focuses on three major types: load-bearing wall materials, insulation materials, and wall cladding materials. A comparison is made for the GWP values and circularity potential of these materials under the four building construction variants. GWP is measured in [kg CO_2-eq./m^2-external wall] for different load-bearing materials and wall cladding materials, while for insulation materials, it is essential to note that the thickness of each insulation material must be calculated separately. This requirement ensures that each square meter of the external wall achieves the same insulation effect (i.e., achieving the same U-value). The recycling potential values are measured in [%] for all these materials.

Microsoft Excel is used as the primary tool for data recording, comprehensive analysis, and visualization. The visualization will mainly be achieved through constructing scatter plots and combo charts. Combo charts will display values and trends of GWP and UMI across different levels within the same visual representation, while scatter plots assess the relationship between the two variables by placing them on the X and Y axes. Additionally, adding trend lines in both charts facilitates a precise observation of outliers, aiding in a better understanding of the relationship between the variables.

To delve deeper into the analysis of the correlation between the two variables, besides using scatter plots and combo charts, this study also incorporates statistical correlation coefficient calculations to quantify their relationship. This study uses the Spearman rank correlation coefficient (rho, ρ). By combining these visualization and statistical tools, the study aims to provide a multi-faceted analysis of the correlation between UMI and GWP.

3.1.1. Spearman Rank Correlation Coefficient (rho, ρ)

Due to the non-linear relationship between the two variables under investigation in this study, the Spearman rank correlation coefficient is employed. The Spearman correlation coefficient provides information about the strength and direction of the relationship between two variables. Figure 3-2 illustrates the possible range of correlation coefficient values. Its range extends from -1 to 1, where a positive value indicates that as one variable increases, the other variable also monotonically increases, a negative value indicates that as one variable increases, the other variable monotonically decreases, and a value of 0 indicates no monotonic relationship between the two variables (Gogtay & Thatte, 2017). Additionally, significance (p-value) is a critical component in correlation coefficient analysis, representing the reliability of the correlation analysis. If the p-value is greater than 0.05, it suggests that the evidence is insufficient to reject the null hypothesis, implying that there is no statistically significant relationship between the two variables.

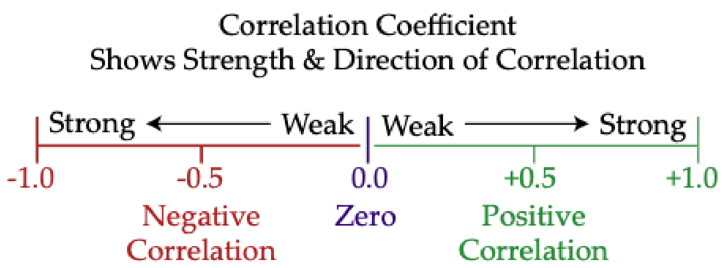


Figure 3-2: Range of correlation coefficient (Gogtay & Thatte, 2017)

3.2. Research Project ECO+

The research project ECO+, situated in the Debring-Stegaurach area near Bamberg, focuses on the redevelopment of an underutilized wasteland spanning approximately 6,000 m^2. The objective of the project is to develop and assess a planning method that fosters positive ecological impacts within neighborhoods and cities. By transforming the area into a residential area spanning 3,000 to 5,000 m^2, this project aims to address the central question: "How can urban development be implemented positively according to sociological, ecological, economic, and aesthetic aspects?" This study proposes a holistic approach to urban development that considers multiple aspects of accelerating ecological change and sustainability in the building sector. Researchers and individuals involved in actual project planning aim to benefit various aspects of urban development, including ecological, economic, and social aspects in the fields of society, energy, materials, greening, water, and transportation.

To achieve this goal, the research team embarked on a thorough selection process, evaluating a wide range of architectural draft concepts. Ultimately, they focused on Variant 7 for further evaluation and optimization. Variant 7 comprises two residential blocks, one parking building, 26 parking spaces, and 24 residential units. The total floor area, excluding the parking building, amounts to 3210 m^2. Additionally, the perimeter areas surrounding the buildings are adorned with green spaces, emphasizing the concept of eco-friendliness and enhancing the overall environmental aesthetics.

In parallel, the research team provided four building construction variants: sand-lime brick, brick, wood massive, and wood light. Figure 3-3 presents the structural cross-sections under each construction option. A detailed analysis of each building component (including foundation, exterior wall, interior wall, window, ceiling, and roof) reveals varying construction structures and layers corresponding to the different structural systems. The structures of foundations, windows, and internal walls are consistent within the two brick construction variants and also show uniformity in the two wood construction variants. The structure of external walls varies according to the four different constructions. As for ceilings and roofs, they have the same structure in the two brick construction variants but differ in the two wood variants, corresponding to their respective construction variants.

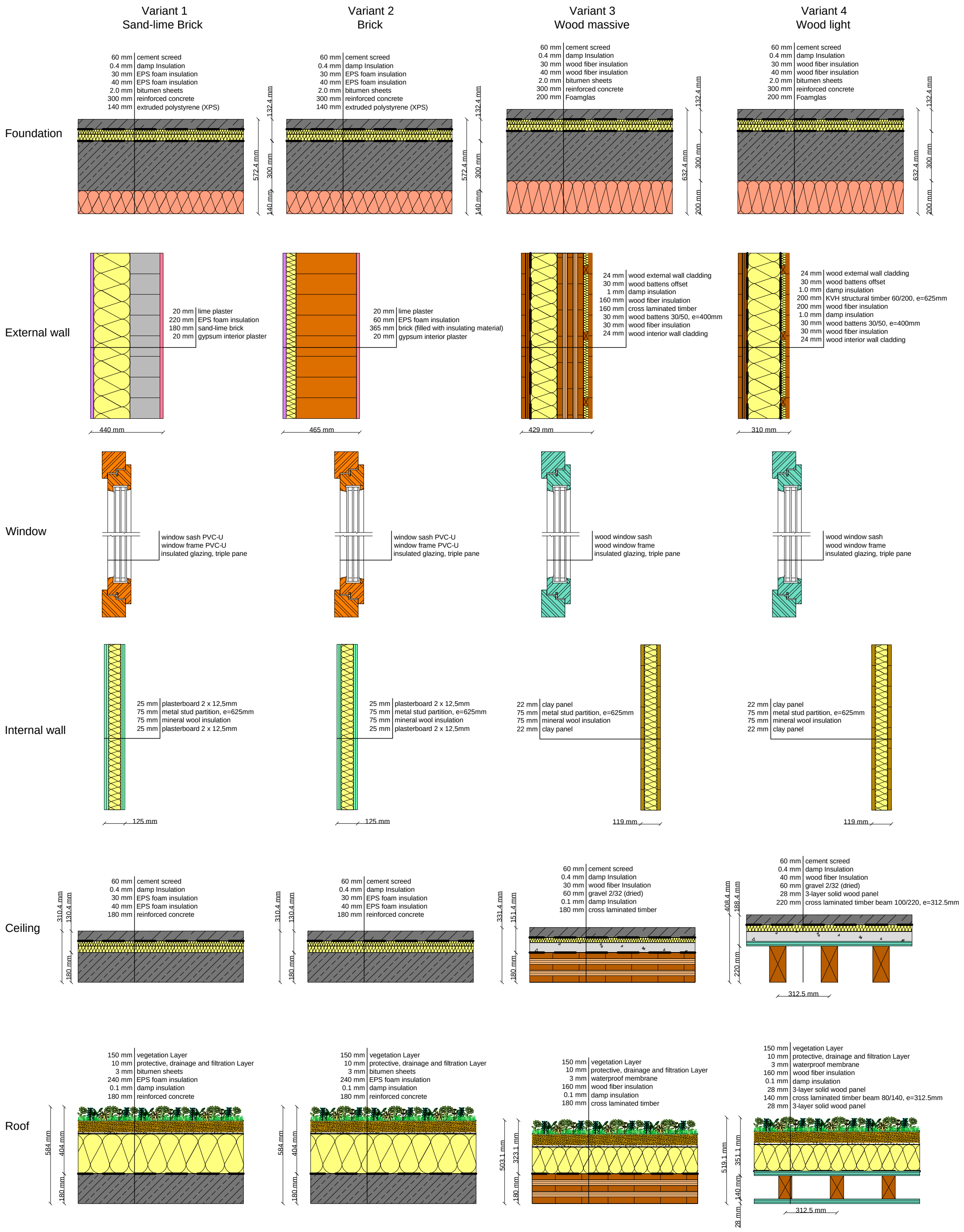


Figure 3-3: Cross section of six building components under different building construction systems: sand-lime brick, brick, wood massive and wood light.

3.3. Life Cycle Assessment Methods

3.3.1. Principle and Framework based on ISO 14040/14044

In response to the increasingly severe environmental issues, ISO established environmental management standards in the 1990s, which are included in its 14000 series of standards (Cabeza et al., 2014). The 14040 series focuses on standardizing the principles and framework of LCA, while the 14044 series emphasizes the requirements and guidelines for LCA. One key focus in ISO 14040 is defining the four essential elements for conducting LCA analysis: goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation, which together form the framework of LCA (Figure 3-4). It is worth emphasizing that LCA is an iterative process, guided by ISO 14040. Each completed step requires revisiting the previous step for validation and refinement to achieve the initial research objectives. According to ISO 14040, the results obtained within the LCA framework provide valuable insights for decision-making processes related to product development and improvement, strategic planning, policy-making, and marketing systems.

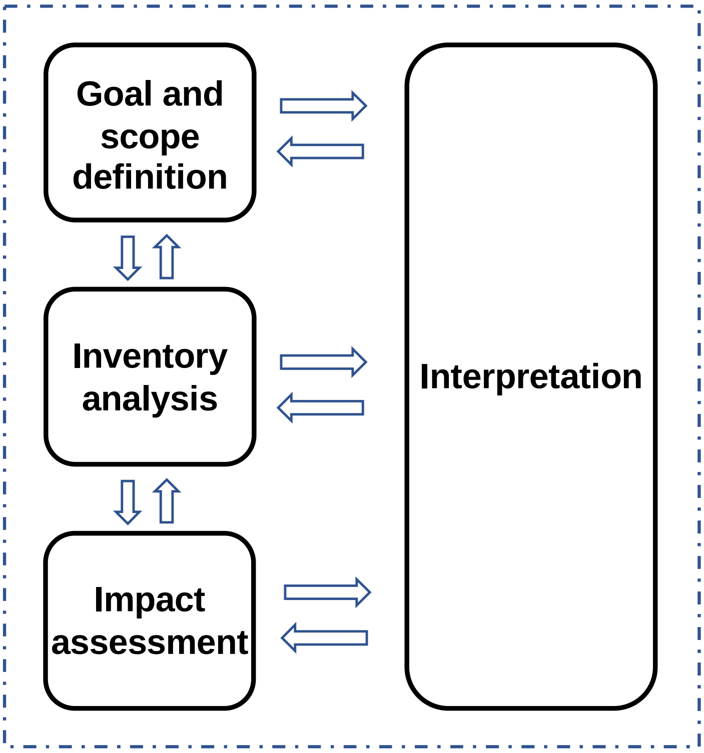


Figure 3-4: LCA framework based on ISO 14040

BUILDING LIFE CYCLE INFORMATION														SUPPLEMENTARY INFORMATION BEYOND THE BUILDING LIFE CYCLE
PRODUCT STAGE			CONSTRUCTION STAGE		USE STAGE					END OF LIFE STAGE				
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	C1	C2	C3	C4	D
Raw material supply	Transport	Manufacturing	Transport	Construction	Use	Maintenance	Repair	Replacement	Refurbishment	De-construction Demolition	Transport	Waste processing	Disposal	Benefits and loads beyond the system boundary Reuse-Recovery-Recycling-Potential
					B6 Operational energy use									
					B7 Operational water use									

Figure 3-5: Life Cycle Phases according to DIN EN 15978

The first step, goal and scope definition, establishes the study’s purpose, object, functional unit, system boundaries, and data quality. The functional unit is a critical aspect as it defines the identified functions of the product, providing a reference for analyzing the inputs and outputs of the system, which facilitates the comparability of LCA results. Additionally, it is crucial to determine the reference flows that fulfill the product's functions. According to Buyle et al. (2013), assessing products based on their functions rather than their physical characteristics is one of the advantages of LCA, enabling comparisons between products with similar functions. Figure 3-5 illustrates the five stages of the building life cycle that must be considered when setting the system boundaries.

The second step, inventory analysis, involves collecting, calculating, and integrating material and energy flows associated with various life cycle stages of the product system. The primary objective of this step is to quantify the inputs and outputs of the target product system.

The third step, LCIA, includes a mandatory component: allocating the results of the second step to selected environmental impact categories and expressing the specific environmental impacts using category indicators. Commonly used impact categories include GWP [kg CO_2-eq.], acidification potential (AP) [kg SO_2-eq.], and total non-renewable primary energy (PENRT) [MJ]. In the context of this study, the primary focus is on GWP, while AP and PENRT are beyond the scope of this discussion.

Finally, in the life cycle interpretation phase, the results obtained from the inventory analysis and LCIA should be used to interpret the final results within the defined research objectives and scope of the research. This phase is crucial for understanding the LCA results, analyzing the limitations of the study, and providing subsequent recommendations.

3.3.2. Principle of Global Warming Potential

GHGs contribute to global warming by absorbing energy and reducing the rate at which energy is emitted from the atmosphere, with different gases having varied radiative efficiencies and residence times in the atmosphere. The concept of GWP provides a standard metric for quantifying the contribution of different gases to global warming. Specifically, it allows for comparing the amount of energy absorbed by emitting 1 ton of a gas over a specified period (usually 100 years) relative to emitting 1 ton of CO_2. Each gas has a specific GWP value, with higher GWP values indicating a more significant warming potential than CO_2.

3.3.3. Existing Modeling Methods for Allocating the Use of Secondary Materials and End of Life Recycling in Life Cycle Assessment

When the inputs of a considered product system originate from another product's lifecycle, or the outputs of this product system are utilized in another product's lifecycle, the issue arises of how to reasonably allocate the environmental burdens and benefits generated by the input and output processes in LCA (Allacker et al., 2014). This issue has been discussed in the LCA field since the 1990s concerning how to define system boundaries for secondary materials and recycling processes, along with the allocation issues arising from them (Allacker et al., 2014; Ekvall et al., 2020). Although ISO 14044 provides a conceptual framework aimed at guiding practitioners and researchers on how to model the EoL phase, there is currently no unified, widely recognized method for modeling recycling in LCA (Allacker et al., 2014; Ekvall et al., 2020). The following are two existing modeling methods that have been applied internationally:

<u>Simple cut-off approach (also called the recycled-content approach, or the 100-0 method):</u>

This method is recommended by the international Environmental Product Declaration (EPD) system and PAS 2050 (British standard for carbon footprint). It is also considered as one of the simplest methods for modeling recycling in LCA (Ekvall et al., 2020). The international EPD system defines the boundary of the product life cycle, which should be where the material has its lowest market value, typically is after the material has completed its use phase and before its recycling process (Ekvall et al., 2020). In this case, all the environmental burdens related to the recycling process are allocated to the life cycle where the recycled material is used (Ekvall et al., 2020). The environmental burdens generated by a material throughout its life cycle can be calculated using the following equation (Equation (1)):

$$E = (1 - R_1) \times E_v + R_1 \times E_R + (1 - R_2) \times E_D \tag{1}$$

Where:

- R_1 is the share of recycled material in the product,
- R_2 is the rate of recycling of material after use in the product,
- E_v is the environmental burdens of virgin material production,
- E_R is the environmental burdens of recycling process, and
- E_D is the environmental burdens of the waste disposal.

As shown in Figure 3-6, this method primarily considers emissions related to three aspects of the investigated product:

(1) $(1–R_1) \times E_V$: Emissions generated from the production of primary materials inputs
(2) $R_1 \times E_R$: Emissions from the recycled content inputs during the recycling process
(3) $(1–R_2) \times E_D$: Emissions from the final disposal of the product

When the emissions generated during the recycling process are less than those generated during the production of primary materials ($E_R<E_V$), using a higher proportion of recycled materials in the product results in a reduced overall environmental burden from the product (Ekvall et al., 2020). Furthermore, in scenarios where emissions associated with product disposal are positive ($E_D>0$), a higher recycling rate after the product's use phase leads to a smaller overall environmental burden from the product (Ekvall et al., 2020).

However, for biogenic materials such as wood, there are issues with the cut-off method. The carbon dioxide absorption by wood results in negative emissions during the production of primary materials for these products (E_V<0). This implies that using more recycled materials to produce wood leads to a more significant overall environmental burden from the product, despite the ecological advantages of using recycled wood.

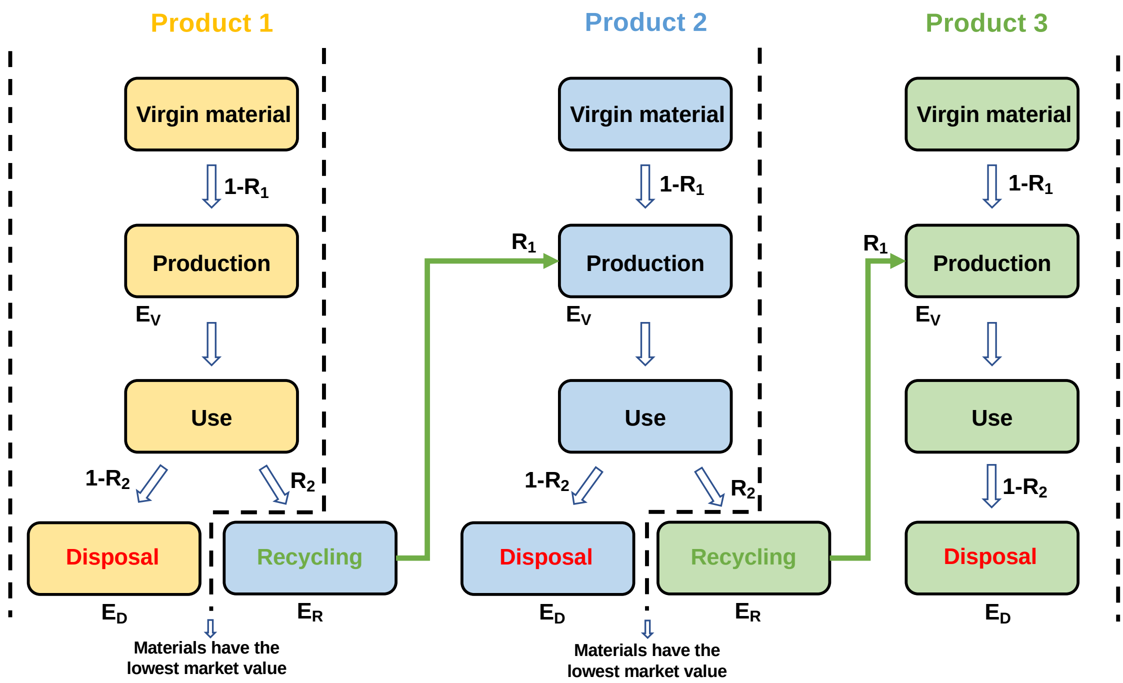


Figure 3-6: Illustration of simple cut-off method in the utilization of building materials across three different product lifecycles through recycling processes (Ekvall et al., 2020)

Cut-off plus credit:

This method is recommended by the European standard EN15804 and the international standard ISO 21930. According to standards, the life cycle of building products is divided into four life cycle stages, which include multiple information modules (Figure 3-5). The LCA results of each model are reported in the EPD of the product. According to ISO 21930, if the investigated product involves recycling processes, environmental supplementary information (Module D) is provided as an option to supplement and provide information about potential burdens and benefits related to recycling beyond the system boundary of the research product. Module D can be calculated using the following equation (Equation (2)):

$$E' = (R_2 - R_1) \times \left(E_{RpostEoW} - E^* \times \frac{Q_{Rout}}{Q_{Sub}}\right) \quad (2)$$

where:

- R_1 is the share of recycled material in the product,
- R_2 is the rate of recycling of material after use in the product,
- $E_{RpostEoW}$ is the environmental burdens of recycling processes that occur after the outflow if recyclable material reaches the end-of-waste state,
- E^* is the environmental burdens of the material replaced through recycling,
- Q_{Rout} is the quality of the recycled material from the life cycle at the point of substitution, and
- Q_{Sub} is the quality of the substituted material.

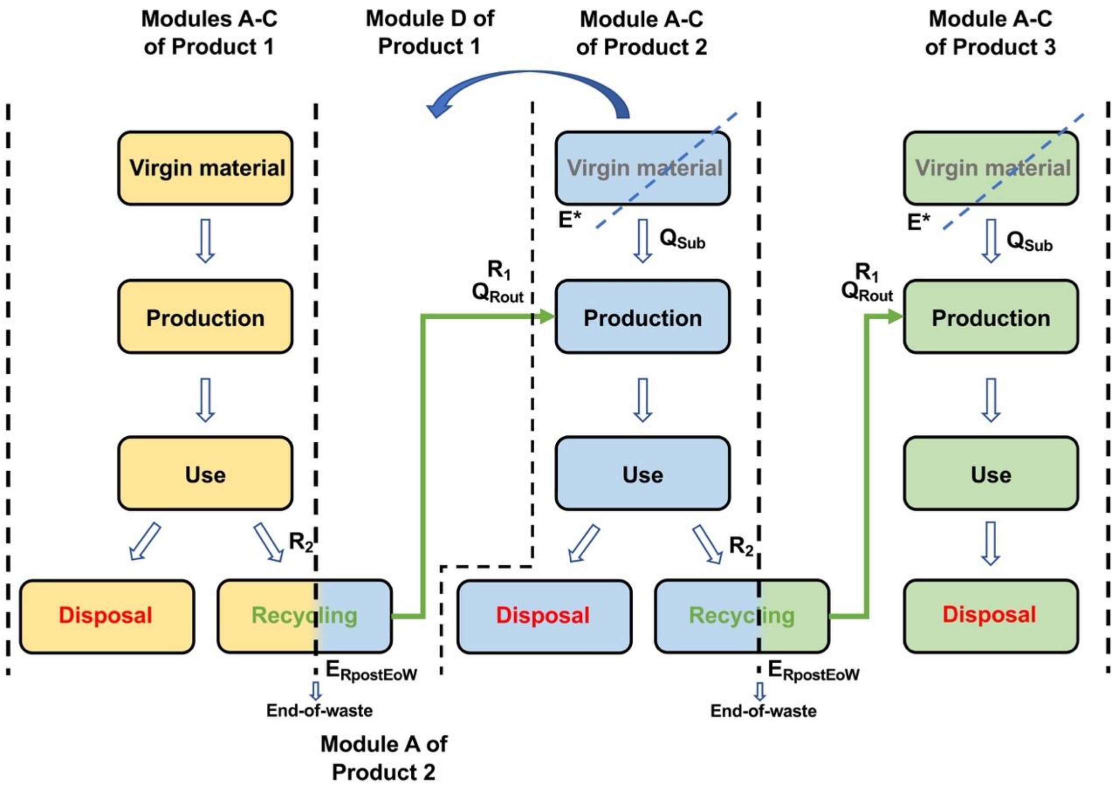


Figure 3-7: Illustration of cut-off plus credit method in the utilization of building materials across three different product lifecycles through recycling processes (Ekvall et al., 2020)

As stated by EN15804, with this approach, the boundary of the EoL stage (Module C) and Module D, which is also the system boundary of the product life cycle, is set at the point where the collected materials for recycling reach the end-of-waste state (Figure 3-7). Recycling processes are allocated separately to the product system, providing recycled materials and subsequent product systems (Ekvall et al., 2020). Processing steps before reaching the end-of-waste state endpoint, such as collection and transportation, are part of the waste processing stage of the investigated product system (Module C3). However, recycled materials that may require further processing after reaching the end-of-waste state endpoint to replace primary materials in subsequent product systems are defined as outside the system boundary and are allocated to Module D. Module D encompasses parts of the recycling processes belonging to the subsequent product system lifecycle and includes the primary material production avoided by recycling (Ekvall et al., 2020). It is worth emphasizing that Module D should not be aggregated with Module A-C when evaluating the environmental impacts of the investigated product; instead, it should be analyzed separately as supplementary information. One reason for this is that part of the recycling processes is considered not only in Module D of the investigated product system but also in Module A of a subsequent product system (Ekvall et al., 2020).

3.3.4. Modification Approach base on the Ökobaudat Database and Existing Methods of Modeling Recycling in Life Cycle Assessment

The Ökobaudat database used in this project is based on European standard 15804+A2. This means that the LCA data for the investigated products in this project are modeled using the cut-off plus credit method. Additionally, the Ökobaudat database considers the use of secondary materials in the production stage (Module A), but the exact proportion of secondary material inputs is unknown. The simulation of the EoL stage (Module C) in Ökobaudat for most products is singular. However, in practice, most products are proportionally recycled and disposed of, implying that the data in Module C of Ökobaudat may not be directly applicable for LCA modeling of the building products studied in this project. To model the LCA of materials according to their future recycling potential, this project implements the following modification equation based on existing modeling methods to adjust the existing Ökobaudat data (Equation (3)):

$$E = E_{A1-A3} + R_2 \times E_{C3} + (1 - R_2) \times E_{C4} \tag{3}$$

Where:

- R_2 is the rate of recycling of material after use in the product,

- $E_{A1\text{-}A3}$ is the environmental burdens of production stage (Module A1 to A3),
- E_{C3} is the environmental burdens of waste processing (Module C3), and
- E_{C4} is the environmental burdens of disposal of waste (Module C4).

The equation primarily encompasses three aspects of environmental burdens: the production process considering the use of secondary materials, the partial recycling processes that occur before the collected waste reaches the end-of-waste state, and the disposal process, as depicted in Figure 3-8. As mentioned in section 3.3.3., certain recycling processes are calculated in both Module D of the investigated product system and Module A of the subsequent product system. Consequently, obtaining the total recycling-related loads from the Ökobaudat dataset is difficult. This includes the entire process from end-of-use phase to the end-of-waste state and from there to the formal replacement of primary materials in the following product system. In this project, data modification is limited to waste processing (Module C3) and waste disposal (Module C4).

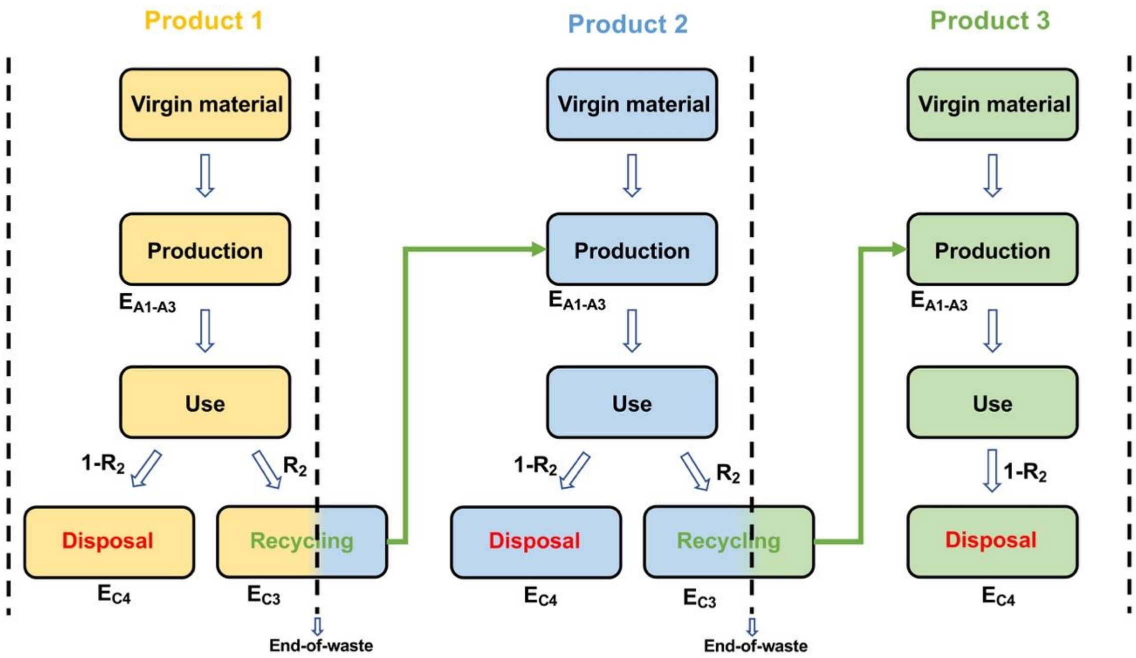


Figure 3-8: Illustration of modified method in the utilization of building materials across three different product lifecycles through recycling processes

3.4. Application of LCA in the Research Project ECO+

3.4.1. Goal and Scope Definition

This LCA analysis presented in this paper aims to select the most optimal construction variant out of the four potential options proposed by the research team, considering only the impact category of GWP. Additionally, the study also seeks to compare the influence of different building construction variants on the LCA outcomes. The primary audience for this paper is students and research team members, primarily for academic purposes, to assess the emissions of different building construction variants in the building sector and subsequently provide optimization recommendations for the research project ECO+.

This LCA focuses on the following building life cycle phases: A1-A3 (raw material supply, transport, manufacturing), B4 (replacement), and C3-C4 (waste processing, disposal). Since in the early design stages, A4-A5 (transport, construction), B1-B3 (use, maintenance, repair), B5-B7 (refurbishment, operational energy use, operational water use), C1-C2 (demolition, transport) will not be considered in this LCA. It should be emphasized that the GWP generated from the production and EoL stage of building materials, which necessitate a replacement during the lifespan of the building, must be accounted for as twice their initial value.

Functional units should be distinguished across different ebene. The primary function of the buildings of the research project ECO+ is to provide living space for residents. Therefore, the functional unit at the building level is [m^2-NGF]. At the building component level, the functional unit is [m^2-component area]. The assumed lifespan of the building is 50 years.

The considered building materials in this study are limited to the following building components: foundation, external wall, window, internal wall, ceiling and roof. Other building components of the target building are outside the scope of this LCA. The research team is responsible for providing the total area of the aforementioned building components. The materials are categorized according to DN276 KG300 to enhance the clarity and visualization of all the materials.

3.4.2. Life Cycle Inventory, Life Cycle Impact Assessment and Interpretation

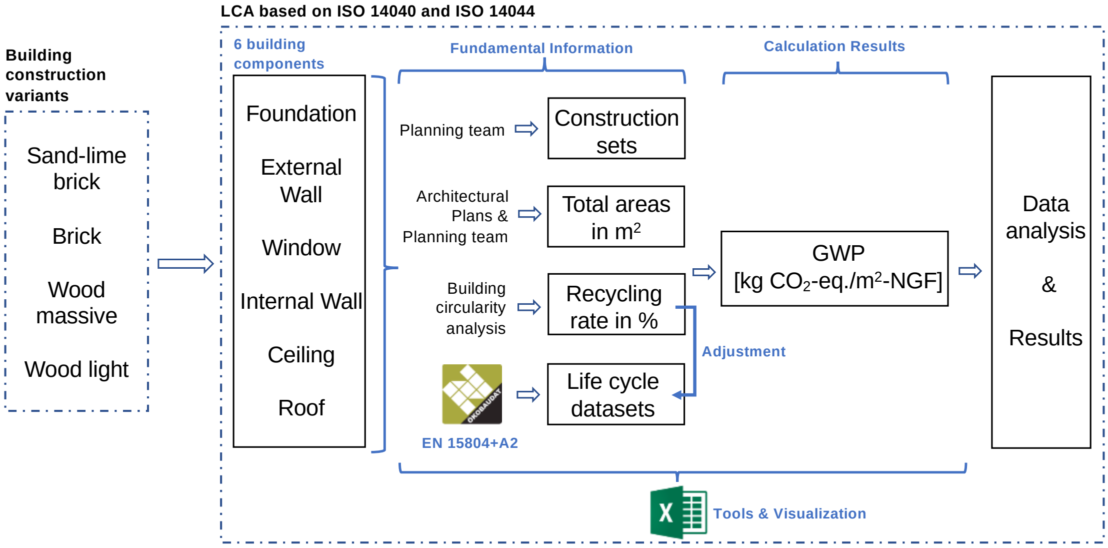


Figure 3-9: Workflow of conducting LCI & LCIA

Figure 3-9 shows that each building component in this study follows a similar process within the LCA framework involving both LCI and LCIA. The focus of the LCI is to create a detailed inventory of inputs and outputs of the product system within the scope of the study. The building construction sets provided by the research team comprise detailed information on the building component composition and dimensions of each building material used for construction under the four building construction variants. Based on this residential building project, the ground floor plan is considered as the standard layout. It is assumed that the floor plans of other building levels replicate the ground floor layout. The total area of each building component is derived from the architectural layout of the standard floor. Figure 3-10 visualizes the standard floor area of different building components in the architectural concept of Variant 7.

As mentioned in section 3.3.4., the LCA needs to consider the recycling rate of the building materials. The GWP values of the building materials on the C3 and C4 stages obtained from Ökobaudat will be adjusted proportionally based on the recycling rate of materials derived from the building circularity potential analysis. The GWP of each material will be calculated based on its unit in the reference flow and then converted to the GWP generated per square meter of building component. By summing the total GWP of each building material, the GWP at the building component level is obtained in [kg CO_2-eq./m^2-building component area]. This process enables the determination of the overall GWP output of the entire building over its life cycle stages within the system boundary. The total GWP of the entire building is the sum of the product of emissions produced per square meter of building components and the total area of the building components. By dividing the total GWP values by the NGF for each variant, the overall GWP results can be obtained in [kg CO_2-eq./m^2-NGF]. As there are four types of building construction variants, a total of four different GWP values are generated.

Microsoft Excel is a key tool in this LCA analysis, as it offers functionalities for data processing and enables the generation of visual charts and graphs, which are crucial for the in-depth analysis of the GWP values of the different construction variants and interpretation of LCA results.

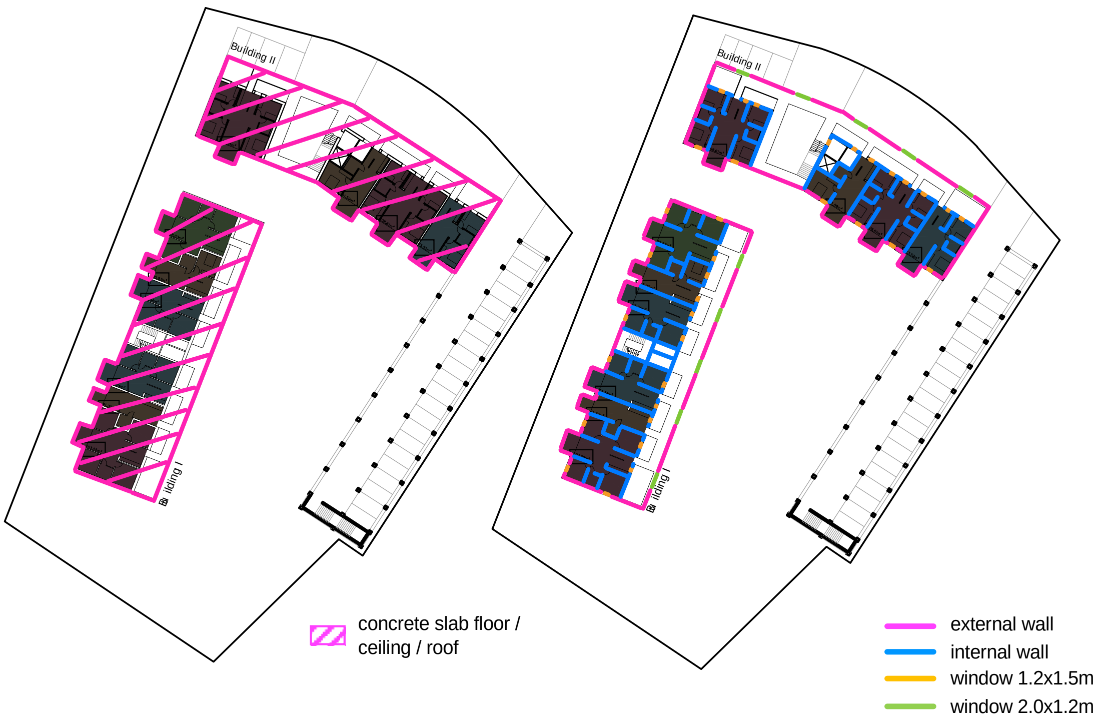


Figure 3-10: Visualization of six building components within the standard floor

3.5. Building Circularity Performance Analysis

In order to address the issue of resource scarcity resulting from population growth under the linear economic model, the circularity performance of buildings needs to be incorporated into new building design standards (Rosen, 2021). Accordingly, the University of Wuppertal has developed an assessment system for quantitatively analyzing the circularity performance of building structures, known as the UMI. UMI provides a framework to measure and evaluate the circularity of new architectural designs, thereby guiding designers to achieve architectural transformation within the context of the CE.

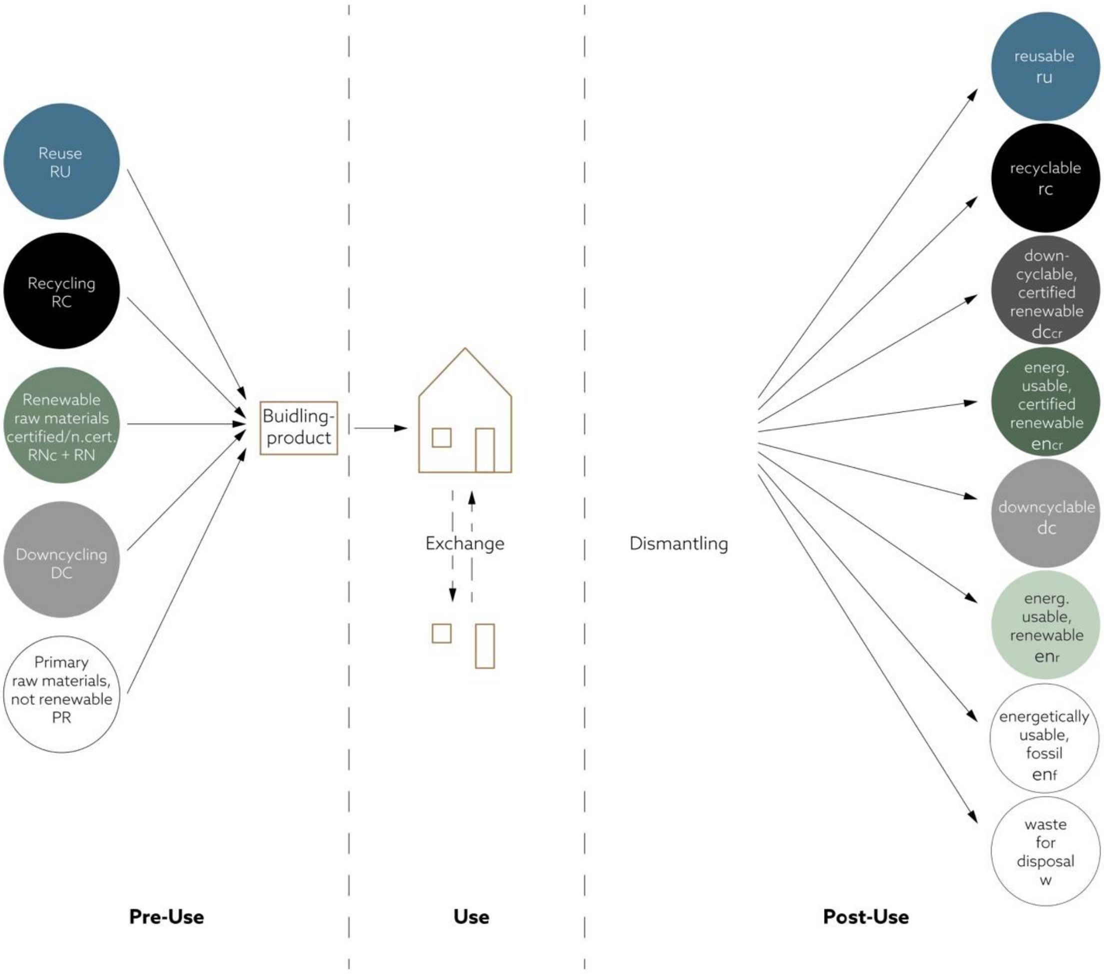


Figure 3-11: Systematics of UMI (Rosen, 2021)

Phase	Quality level	Formula symbol	Circularity potential
Pre-use	Reuse	RU	CLP
	Recycling	RC	CLP
	Renewable	RN	CLP
	Downcycling	DC	LP
	Primary ressources, not renewable	(PR)	-
Post-use	reusables	ru	CLP
	recyclables	rc	CLP
	downcyclables, certified renewable	dc_{cr}	CLP
	energetically usables, certified renewable	en_{cr}	CLP
	downcyclables	dc	LP
	energetically usables, renewable	en_r	LP
	fossil	en_f	-
	disposal	d	-

Loops

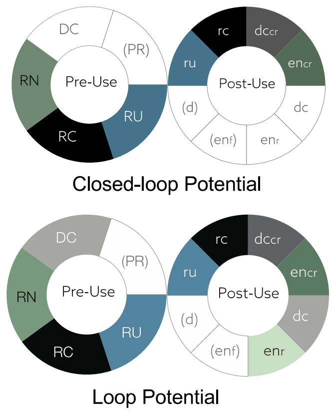


Figure 3-12: Schematic representation of different quality levels of the circular material utilization (Rosen, 2021)

According to Rosen (2021), UMI is derived through the quantification of the share of recycled materials in the total mass of all materials used throughout the lifecycle, which is based on assessing the varying quality levels of circular material utilization before and after the use phase of the building (Figure 3-11). Figure 3-12 illustrates the different quality levels used to evaluate material circularity performance. Materials that can be maintained at a constant quality level within a closed loop, such as reusables, recyclables, and renewable resources, are categorized under “closed-loop potential (CLP).” Materials used in an open loop with a loss in quality, such as downcycling, are categorized under “loop potential (LP).” Non-renewable resources, waste composed of fossil raw materials, and disposal waste should not be included in the circularity potential of materials (Rosen, 2021). To calculate the material’s CLP, Rosen (2021) has developed the following formulas:

$$CLP = CLP_{pre-use} + CLP_{post-use} \tag{4}$$

$$CLP_{pre-use} = RU + RC + RN \tag{5}$$

Where:

- RU is the mass share of reused building components, building elements, or construction products,
- RC is the mass share of recycled materials, and

- RN is the mass share of renewable raw materials.

$$CLP_{post-use} = ru + rc + dc_{cr} + en_{cr} \tag{6}$$

Where:

- ru is the mass share of reusable building components, building elements, or construction products after disassembly,
- rc is the mass share of recyclable materials after demolition, including compost,
- dc_{cr} is the mass share of recyclable materials from certified sustainably grown renewable resources after demolition, and
- en_{cr} is the mass share of energetically usable materials from certified sustainably grown renewable resources after demolition.

At the beginning of a material's life cycle, when it is composed of 100% reused, recycled, or renewable resources, its CLP is considered to be 100%. Similarly, at the end of the material's life cycle, when it is 100% reused, recycled, or sustainably renewable, its CLP is considered to be 100% (Rosen, 2021). A material can achieve a total CLP of 200% when its extraction is sustainable, and it can be fully recycled or renewed after the utilization (Rosen, 2021).

LP considers materials maintaining a constant quality within a closed loop and accounts for materials entering open-loop recycling with quality loss (Rosen, 2021). LP can be calculated using the following formulas:

$$LP = LP_{pre-use} + LP_{post-use} \tag{7}$$

$$LP_{pre-use} = CLP_{pre-use} + DC \tag{8}$$

Where:

- DC is the mass share of downcycled materials.

$$LP_{post-use} = CLP_{post-use} + dc + en_{r} \tag{9}$$

Where:

- dc is the mass share of materials that can be downcycled after demolition, and
- en_r is the mass share of energetically usable materials from renewable resources after demolition.

It is worth noting that both equations (4) and (7) distinguish between two stages: pre-use, which refers to materials before their intended use, and post-use, which refers to materials after their intended use. Different factors influence the assessment of material circularity potential in these two stages. In the pre-use phase, the reusability of materials and the MRC are two parameters influencing material circularity performance. In the post-use phase, the quality level at the EoL stage of materials, the presence of hazardous substances, Material-loop-potential (MLP), and the material's value determine the material's circularity performance (Rosen, 2021).

According to Rosen (2021), in the pre-use phase, MRC is the most critical parameter for quantifying material circularity. MRC refers to the proportion of recycled materials and/or renewable raw materials in the composition of materials. One of the critical requirements for building materials of high circularity performance is a low proportion of non-renewable resources and a high proportion of recycled and/or renewable raw materials during the production phase (Rosen, 2021). Current MRC values for building materials can be accessed from the publicly available database provided by Atlas Recycling.

In the post-use phase, material circularity performance should be assessed from three perspectives: the material level, the structural level, and the economic level (Rosen, 2021). On the material level, the materials' EoL scenario must first be assessed. This assessment involves both high-grade and low-grade EoL scenarios, determining whether the material falls under "CLP" or "LP". Consequently, reusable and recyclable materials include both a high-grade EoL scenario of selective dismantling and a low-grade EoL scenario of usual dismantling can be calculated using the following formulas:

$$rc = rc_{sd} + rc_{ud} \tag{10}$$

Where:

- rc_{sd} is the mass share of recyclable materials in the high-grade EoL scenario of selective dismantling, and

- rc_{ud} is the mass share of recyclable materials in the low-grade EoL scenario of usual dismantling.

$$dc_{cr} = dc_{cr_{sd}} + dc_{cr_{ud}} \tag{11}$$

Where:

- $dc_{cr_{sd}}$ is the mass share of recyclable materials from certified sustainably grown renewable resources in the high-grade EoL scenario of selective dis-mantling, and

- $dc_{cr_{ud}}$ is the mass share of recyclable materials from certified sustainably grown renewable resources in the low-grade EoL scenario of usual dismantling.

$$dc = dc_{sd} + dc_{ud} \tag{12}$$

Where:

- dc_{sd} is the mass share of materials that can be downcycled in the high-grade EoL scenario of selective dismantling, and

- dc_{ud} is the mass share of materials that can be downcycled in the low-grade EoL scenario of usual dismantling.

The following formulas predict the likelihood of materials reaching their respective high-grade EoL scenario of selective dismantling:

$$ru = \frac{M_{ru} \times f_W \times f_V}{M} \times 100 \tag{13}$$

$$rc_{sd} = \frac{M_{rc} \times f_W \times F_V \times MLP}{M} \times 100 \tag{14}$$

$$dc_{cr_{sd}} = \frac{M_{dccr} \times f_W \times f_V}{M} \times 100 \tag{15}$$

$$dc_{sd} = \frac{M_{dc} \times f_W \times f_V}{M} \times 100 \tag{16}$$

Where:

- M_{ru} is the mass of reusable construction materials,
- M_{rc} is the mass of recyclable materials,
- M_{dccr} is the mass of recyclable materials from certified sustainably grown renewable resources,
- M_{dc} is the mass of materials that can be downcycled,
- f_W is factor work,
- f_V is factor value,
- M is the mass of the input material, and
- MLP is the Material-Loop-Potential.

Work	Quintile	Evaluation	Factor (f_w)
	I	very low	1,0
7,1 MJ/m^2			
	II	low	0,9
8,7 MJ/m^2			
	III	medium	0,8
11,5 MJ/m^2			
	IV	high	0,7
12,6 MJ/m^2			
	V	very high	0,6

Figure 3-13: Scale for the evaluation of the deconstruction effort (Rosen, 2021)

The likelihood of materials reaching a high-grade EoL scenario needs to be analyzed from structural and economic perspectives. At the structural level, circular performance of the materials should be evaluated based on the ease of disassembling building components and the feasibility of obtaining individual parts, as these are crucial factors influencing the material's potential to achieve a high-grade EoL scenario (Rosen, 2021). To account for the effort required to disassemble each square meter of building component area and separate individual parts, the parameter "work" is used as a coefficient "f_w" in formulas (13) to (16). As depicted in Figure 3-13, the effort required for deconstruction per square meter of the component area is divided into five levels, ranging from very low to very high. As the effort increases, the probability of recovering single-type materials decreases.

From an economic perspective, the value of materials and the expenses associated with obtaining individual parts determine whether materials achieve high-grade and low-grade EoL scenarios, and these are measured using the parameter "value" as the coefficient "f_v" (Rosen, 2021). The higher the material's value and the lower the associated costs, the greater the likelihood of achieving a high-grade EoL scenario (Figure 3-14). Furthermore, in the post-use phase, MLP is a significant parameter for assessing material circularity performance. MLP refers to the ideal maximum proportion of circular materials achieved under continuous technological improvements during production. When evaluating closed-loop potential, MLP represents the maximum amount of circular materials to be input into the production of that material, which implies that if the recycled secondary materials exceed this limit, the remaining secondary materials will either be downcycled or disposed of (Rosen, 2021).

Price	Evaluation	Factor (f_v)
	extremely positive	1,3
880 €/t		
	very high positive	1,2
420 €/t		
	high positive	1,1
150 €/t		
	slightly positive	1,0
0 €/t		
	slightly negative	0,9
-23 €/t		
	high negative	0,8
-54 €/t		
	very high negative	0,7
-146 €/t		
	extremely negative	0,6

Figure 3-14: Scale for the evaluation of selective deconstruction on the material value and associated costs (Rosen, 2021)

3.6. Application of Urban Mining Index in the Research Project ECO+

3.6.1. Calculation of Urban Mining Index on the Building Component Level

As shown in Figure 3-15, to compare the circularity potential of the four different building construction variants within the research project ECO+, the circularity performance assessment system described in Section 3.5. is applied to six building components of the four construction variants. The tool used for calculations is an Excel spreadsheet developed by Rosen for system calculations and circularity performance assessment. This Excel table provides flexibility in adjusting data for different building components by adding formulas and helps users visualize the results through charts for analysis.

The first step of the calculation involves recording and quantifying building materials. The six building components and the materials used in each layer of these components are categorized and numbered according to DIN276 KG300 to standardize the format and facilitate subsequent calculations. Users are required to manually input the connection methods for each layer of building components to assist in assessing the effort needed for future dismantling. Since the research team did not specify the connection methods for the materials used in this project, the most commonly used connection methods for each material are applied in the calculations. It is essential to note that the calculation unit for each building component is its mass per square meter, i.e., mass/m^2, which allows designers to compare different variants of building components in early design stages when the total area of building components is unknown (Rosen, 2021). The mass per square meter of a building component is calculated as the sum of the masses of all materials that constitute the component on a unit area basis. The mass of these building materials can be automatically calculated in Excel based on density and the known thickness of each building material. If a building material needs replacement within the project's building lifecycle, the mass per square meter of the building material must be multiplied by the number of replacements to obtain the total mass per square meter of the building component over 50 years.

The second step is determining the mass shares of each building material at different quality levels during the pre-use phase. In this step, users must manually input the mass shares of each building material at different quality levels based on their MRC, which can be obtained from the Atlas Recycling database. The mass of materials at different quality levels can be determined by multiplying the total mass of each building material by the corresponding mass share. By dividing the sum of the masses at each quality level by the total mass of the building component over its entire lifecycle, the mass contribution percentage at each quality level for that building component will be generated.

The next step is to determine the coefficients f_w and f_v. The coefficient f_w is determined based on the component catalog summarized in Rosen's UMI Chapter 6.5. The coefficient f_v is determined based on Figure A6.4 in Rosen's UMI. If data for a particular building material cannot be obtained from these sources, it can be approximated by referencing similar structural layers from the calculation examples in Rosen's UMI Chapter 8. The economic factor f is obtained by multiplying f_w and f_v, representing the likelihood of achieving a high-grade EoL scenario for the building materials.

Assessing the EoL scenario for building materials in the post-use phase is an essential step. As most materials currently do not have stable reuse markets, the possibility of reuse is not considered in the assessment. Furthermore, the calculation assumes that all materials are free from hazardous substances. The assessment of high-grade and low-grade EoL scenario is determined based on Figure A5.4 in Rosen's UMI. If a material can be recycled in the high-grade EoL scenario, the MLP of this material must be considered, which can be obtained from the Atlas Recycling database.

Calculations for high-grade and low-grade EoL scenarios should be conducted separately. The mass of a material that can achieve a high-grade EoL scenario through selective dismantling is obtained by multiplying the total mass of the material over the entire lifecycle by the economic index f, considering MLP when necessary, and inputting it under the corresponding quality level. The remaining mass of the material is allocated to the low-grade EoL scenario. The mass share contribution of each building material at each quality level is calculated by adding the mass of high-grade and low-grade EoL scenarios under each quality level and dividing it by the total mass of this building material. The mass share of each building component at each quality level is determined by dividing the sum of material masses at high-grade and low-grade EoL scenario under each quality level by the total mass of all materials used in that building component.

Finally, the calculations of CLP and LP are performed, distinguishing between the pre-use and post-use phases. In the pre-use phase, CLP is obtained by adding the mass share under the quality levels of reuse, recycling, and renewable categories. LP is obtained by adding the mass share under the quality levels of reuse, recycling, renewable, and downcycling. In the post-use phase, CLP is calculated by adding the mass share under the quality levels of reuse, recycling, and certified sustainable utilization. LP is calculated by adding the mass share under the quality levels of reuse, recycling, certified sustainable utilization, downcycling, and energy utilization from renewable resources. The total CLP value for each building component is obtained by adding the CLP values of the pre-use and post-use phases, and the total LP value is obtained by adding the LP values of the pre-use and post-use phases.

3.6.2. Calculation of Urban Mining Index on the Building Level

To calculate the UMI accurately on the building level, the calculation of the total mass of each building component is required, which is achieved by multiplying its total area by the mass per square meter. Subsequently, by adding the mass of each building component, the total mass of the entire building over its lifecycle can be determined.

The UMI on the building level is derived through a weighted calculation of the CLP and LP in the pre-use and post-use stages. The critical aspect lies in the different weighting assessments required for open-loop and closed-loop recycling. Due to the partial quality loss of the materials in open-loop recycling, only half of their mass is considered in the UMI calculation, weighted with a coefficient of 0.5. In contrast, closed-loop recycling is without quality loss and includes its total mass in the UMI computation. Moreover, this study assumes that the impacts on the building's overall circularity potential are equal in the pre-use and post-use stages, hence applying a coefficient of 0.5 for both stages. Finally, the UMI value on the building level is obtained by summing the products of each building component's weighted circularity potential value and its mass proportion.

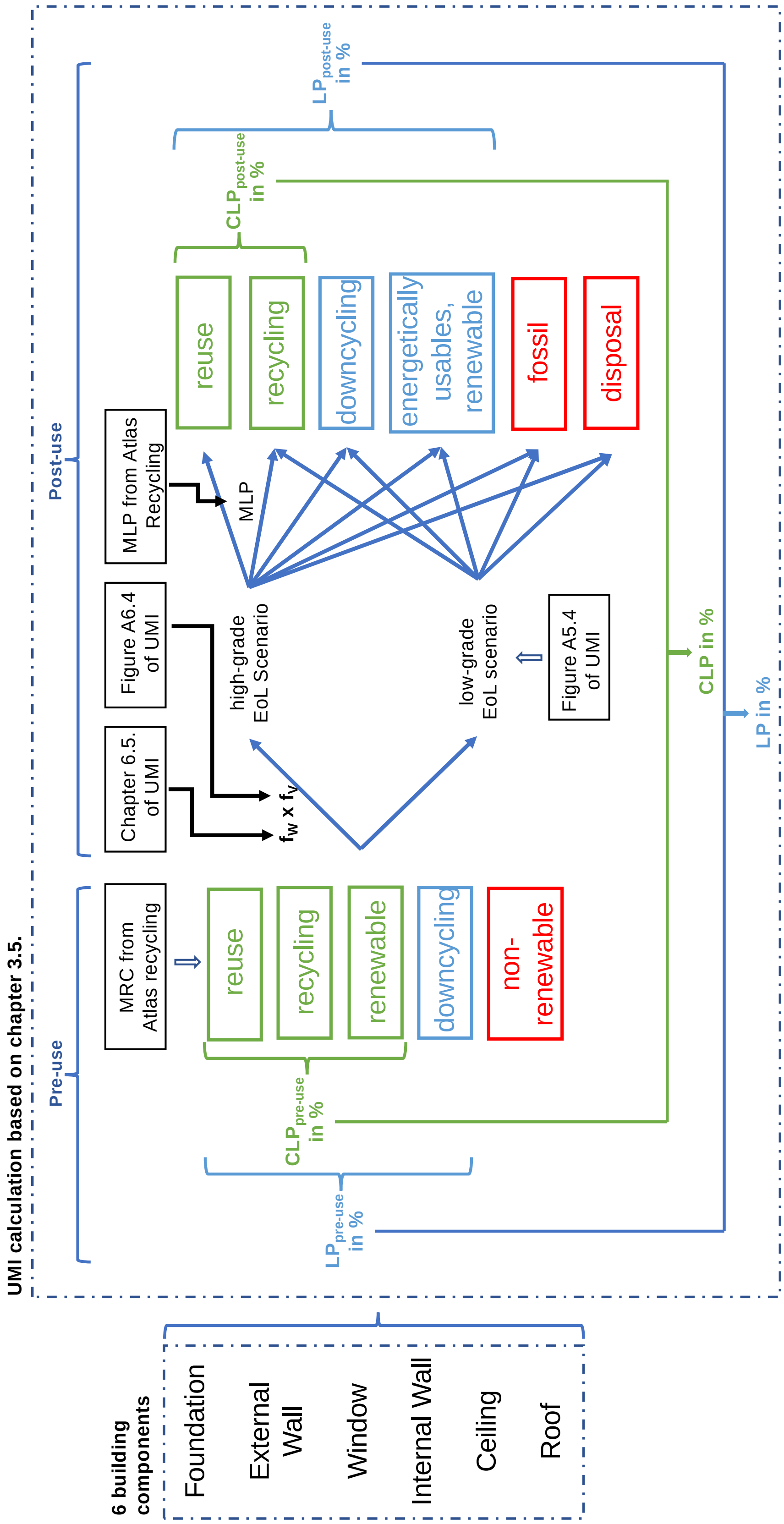


Figure 3-15: Workflow of calculating the CLP and LP for six building components of four building construction variants in the research project ECO+ base on the chapter 3.5.

4. Results and Analysis

4.1. Results and Analysis of Life Cycle Assessment

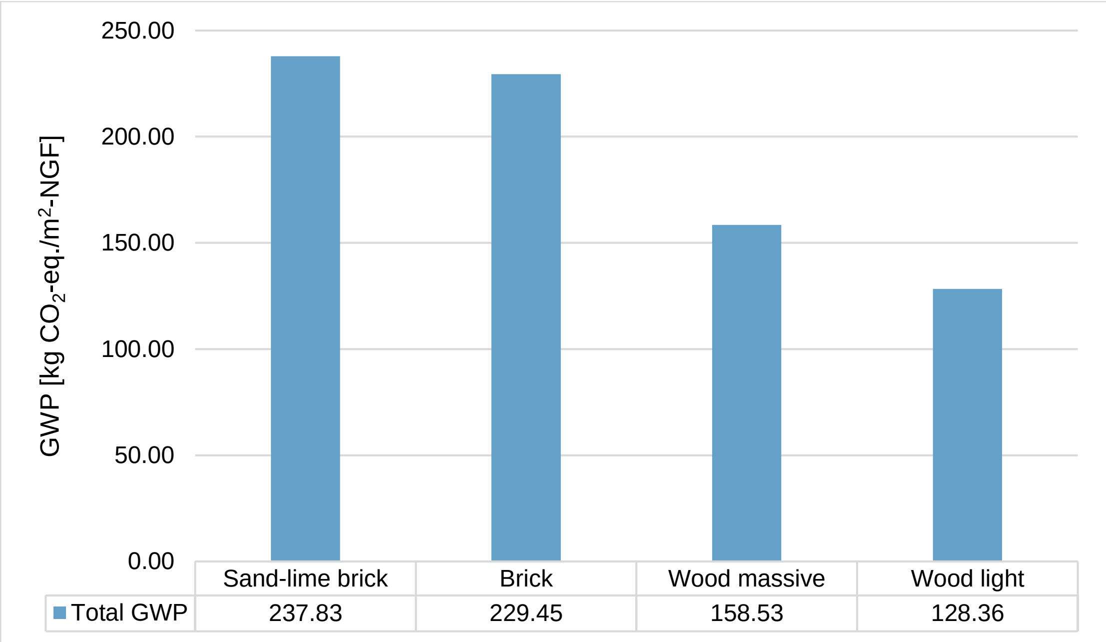


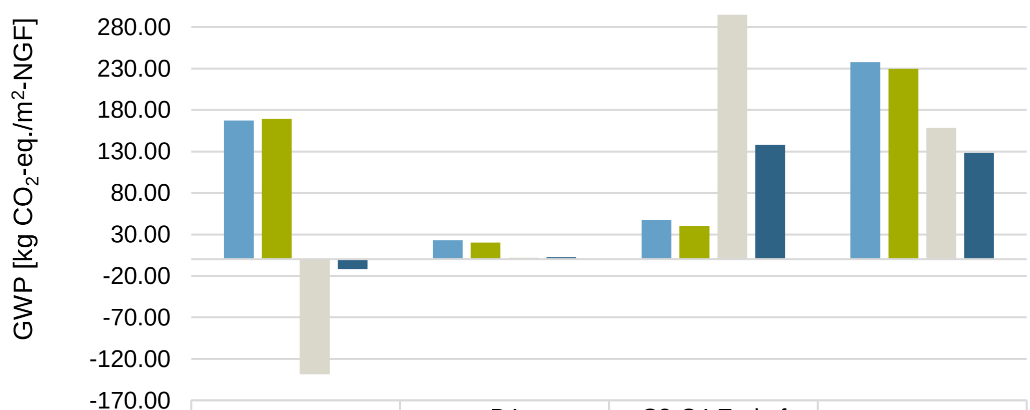
Figure 4-1: Total GWP of the building [kg CO_2-eq./m^2-NGF] under four construction variants

Figure 4-1 presents the total GWP values of the building under four building construction variants. Among these four investigated variants, the GWP of the wood constructions is generally lower than that of the brick constructions. The light wood construction has the lowest GWP of 128.36 [kg CO_2-eq./m^2-NGF], while the massive wood construction is responsible for 158.53 [kg CO_2-eq./m^2-NGF], 24% higher than the light wood construction. In brick constructions, the total GWP of the regular brick construction and the sand-lime brick construction is similar, with the sand-lime brick construction having the highest total GWP of 237.83 [kg CO_2-eq./m^2-NGF], followed by the regular brick construction of 229.45 [kg CO_2-eq./m^2-NGF]. The total GWP of building under the sand-lime brick or the regular brick constructions is approximately 1.8 times higher than under the light wood construction.

The difference in GWP between the sand-lime brick and the regular brick construction is mainly reflected in the external wall, with other building components of these two constructions being structurally same. The external wall under the sand-lime brick construction is responsible for 104.8 [kg CO_2-eq./m^2-external wall], with the two most significant contributing materials being the EPS insulation and the sand-lime bricks, each accounting for 41% of the GWP of one square meter external wall area. The external wall under the regular brick construction has a GWP of 81.89 [kg CO_2-eq./m^2-external wall], 22% less than the sand-lime brick construction, with the most significant contributing material being the bricks, accounting for 63% of the GWP of one square meter external wall area. The bricks have a GWP of 8 [kg CO_2-eq./m^3] higher than sand-lime bricks and require 185 mm more thickness. However, this increased GWP is offset by the lower insulation thickness needed for the external wall under the regular brick construction, which is 160 mm thinner than the sand-lime brick construction, resulting in a lower GWP of the external wall with the regular brick construction.

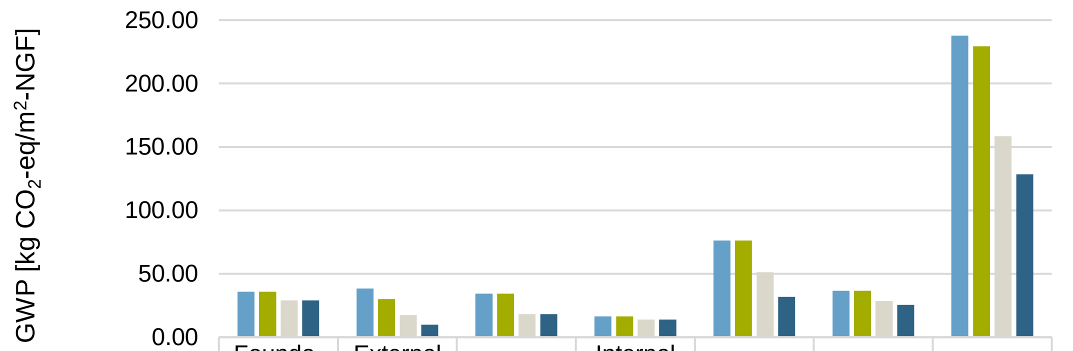
The difference in GWP between the massive and the light wood construction is primarily observed in the external wall, ceiling, and roof structure. The KVH structural timber used in the external wall under the light wood construction is responsible for 89 [kg CO_2-eq./m^3], while the cross-laminated timber used in the external wall under the massive wood construction has a GWP of 157.4 [kg CO_2-eq./m^3]. The volume of wood used under the light wood construction is much less than that used in the massive wood construction for one square meter ceiling and roof, resulting in a lower GWP of these two building components under the light wood construction than the massive wood construction.

GWP classified by life cycle stage under the four construction variants is shown in Figure 4-2. For the sand-lime brick construction, the production stage (A1-A3) is responsible for 167.54 [kg CO_2-eq./m^2-NGF], representing 70% of the total GWP, with a GWP of 22.78 [kg CO_2-eq./m^2-NGF] generated in the replacement stage (B4) corresponding to 10% of the total GWP, and a GWP of 47.52 [kg CO_2-eq./m^2-NGF] generated in the EoL stage (C3-C4), accounting for 20% of the total GWP. The distribution of the GWP of the regular brick construction is similar to the sand-lime brick construction, with a GWP of 169.34 [kg CO_2-eq./m^2-NGF] in the production stage (A1-A3), accounting for 74% of the total GWP, a GWP of 20.03 [kg CO_2-eq./m^2-NGF] in the replacement stage (B4), representing 9% of the total GWP, and a GWP of 40.08 [kg CO_2-eq./m^2-NGF] in the EoL stage (C3-C4) corresponding to 17% of the total GWP. In contrast, the main contributor to GWP for the wood constructions is the EoL stage (C3-C4). The EoL stage of the massive wood construction is responsible for 294.88 [kg CO_2-eq./m^2-NGF], while the light wood construction has a GWP of 138.10 [kg CO_2-eq./m^2-NGF] in this stage. The massive wood construction contains more wood volume than the light wood construction, allowing them to store more carbon in the production stage (A1-A3) and, similarly, release more carbon in the EoL stage (C3-C4). The GWP of the two brick constructions in the replacement stage (B4) is greater than the two wood constructions, as carbon storage is considered in the wood constructions.



	A1-A3 Product	B4 Replacement	C3-C4 End of life	Total
Sand-lime brick	167.54	22.78	47.52	237.83
Brick	169.34	20.03	40.08	229.45
Wood massive	-138.45	2.09	294.88	158.53
Wood light	-12.00	2.26	138.10	128.36

Figure 4-2: GWP [kg CO2-eq./m2-NGF] classified by life cycle stage under four construction variants



	Founda-tion	External Wall	Window	Internal Wall	Ceiling	Roof	Total
Sand-lime brick	35.97	38.33	34.29	16.35	76.35	36.54	237.83
Brick	35.97	29.95	34.29	16.35	76.35	36.54	229.45
Wood massive	29.08	17.45	18.25	13.96	51.19	28.59	158.53
Wood light	29.08	9.82	18.25	13.96	31.70	25.55	128.36

Figure 4-3: GWP [kg CO2-eq./m2-NGF] classified by the building component under four construction variants

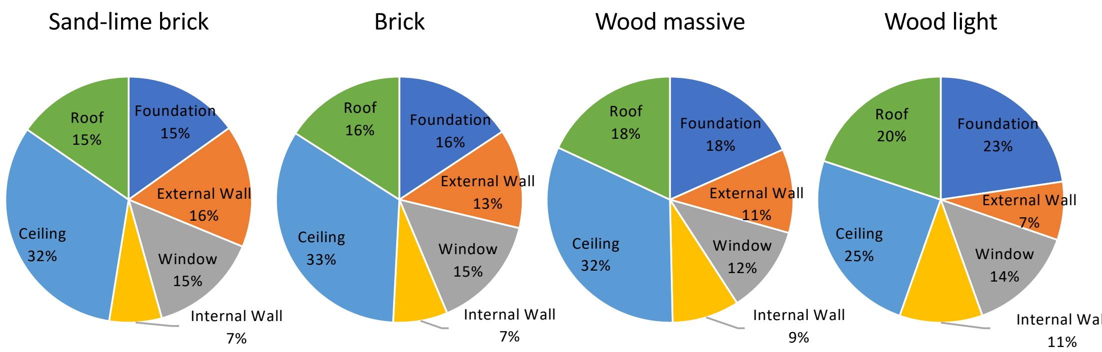


Figure 4-4: Percentage distribution of six building components under four construction variants

Figures 4-3 and 4-4 respectively show the GWP values and percentage distribution of the six building components under four construction variants. The two building components that have the most significant impact on the total GWP of the sand-lime brick construction are the ceiling and the external wall, with the ceiling responsible for 76.35 [kg CO_2-eq./m^2-NGF], representing 32% of the total GWP, and the external wall has a GWP of 38.33 [kg CO_2-eq./m^2-NGF], corresponding to 16% of the total GWP. The remaining part is distributed among the roof (15%), foundation (15%), window (15%) and internal wall (7%). The ceiling under the regular brick construction has a GWP of 76.35 [kg CO_2-eq./m^2-NGF], equivalent to 33% of the total GWP, while the roof is responsible for 36.54 [kg CO_2-eq./m^2-NGF], representing 16% of the total GWP and the foundation is responsible for 35.97 [kg CO_2-eq./m^2-NGF] corresponding to 16% of the total GWP. The remaining part is shared by the windows (15%), external wall (13%), and internal wall (7%). In the massive wood construction, the ceiling has a GWP of 51.19 [kg CO_2-

eq./m^2-NGF], accounting for 32% of the total GWP, while the foundation has a GWP of 29.08 [kg CO_2-eq./m^2-NGF], making up 18% of the total GWP, and the roof has a GWP of 28.59 [kg CO_2-eq./m^2-NGF], representing 18% of the total GWP. The remaining part is distributed among the window (12%), external wall (11%), and internal wall (9%). The ceiling under the light wood construction is responsible for 31.7 [kg CO_2-eq./m^2-NGF], constituting 25% of the total GWP, followed by the foundation, which is responsible for 29.08 [kg CO_2-eq./m^2-NGF] to the GWP, making up 23% of the total GWP, and the roof is responsible for 25.55 [kg CO_2-eq./m^2-NGF] representing 20% of the total GWP. The window, internal, and external wall accounts for 14%, 11% and 7% of the total GWP, respectively.

The ceiling is the building component with the most significant impact on the total GWP among the four building construction variants. The structures of the ceiling are the same in both brick constructions, using reinforced concrete and cement heavily. The reinforced concrete is responsible for 54.58 [kg CO_2-eq./m^2-ceiling area], accounting for 61% of the GWP per square meter of the ceiling, and cement is responsible for 27.49 [kg CO_2-eq./m^2-ceiling area], making up 31% of the GWP per square meter of the ceiling. The load-bearing material of the ceiling is replaced by wood in both wood constructions, resulting in a lower GWP per square meter of the ceiling than brick constructions, with the GWP of ceiling under the massive wood construction being 33% lower than that of brick constructions and the GWP of ceiling under the light wood construction being 58% lower. Cross-laminated timber used in the massive wood construction is responsible for 28.33 [kg CO_2-eq./m^2-ceiling area], accounting for 47% of the total GWP per square meter of the ceiling, while cement screed is responsible for 27.49 [kg CO_2-eq./m^2-ceiling area], representing 46% of the total GWP per square meter of the ceiling. Cement screed used in the ceiling under the light wood construction is the material contributing the most to the GWP of the ceiling, being responsible for 27.49 [kg CO_2-eq./m^2-ceiling area], accounting for 74% of the total GWP per square meter of the ceiling.

4.2. Results and Analysis of Circularity Potential Analysis

4.2.1. Results on the Building Level

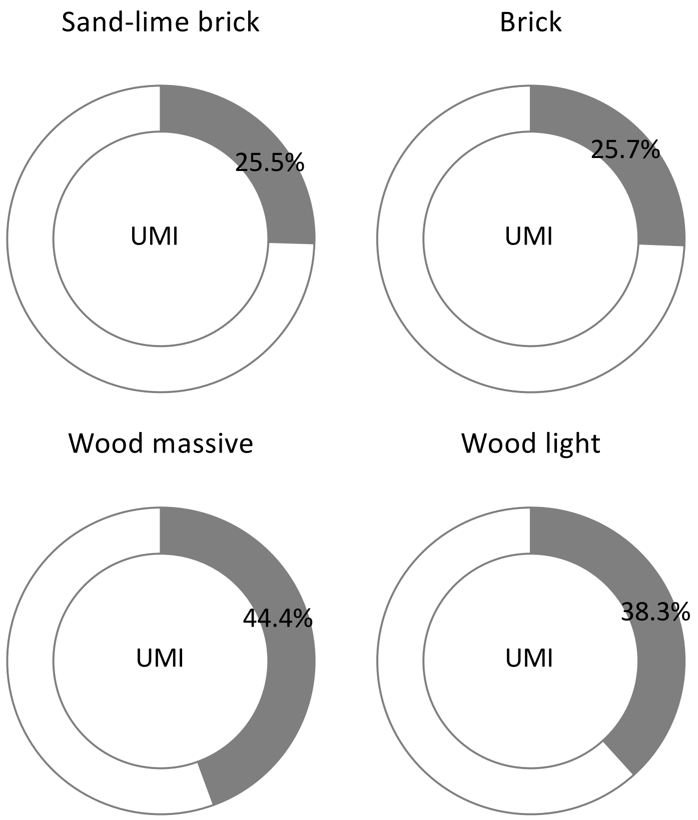


Figure 4-5: Circularity potential of the four construction variants on the building level, expressed in the form of UMI

Figure 4-5 illustrates the circularity potential of the four construction variants on the building level. Among the four investigated constructions, the building under the massive wood construction exhibits the highest circularity potential, with a UMI of 44.4%. In contrast, the building under the sand-lime brick construction has the lowest circularity potential, with a UMI of only 25.5%. Overall, the circularity potential of the building under the wood constructions is superior to that of the brick constructions. The circularity potential of the building under the sand-lime brick construction and the regular brick construction is almost the same, with UMI of 25.5% and 25.7%, respectively, showing a minimal difference of only 0.2%. The UMI of the building under the massive wood construction is higher than that under the brick constructions, with a difference of 19%. Similarly, the building under the light wood construction has a higher UMI than the brick constructions, with a difference of 13%. Moreover, the circularity potential of the building under the massive wood construction is more significant than that under the light wood construction, with their UMI differing by 6.1%.

4.2.2. Results on the Building Component Level

Foundation G-01

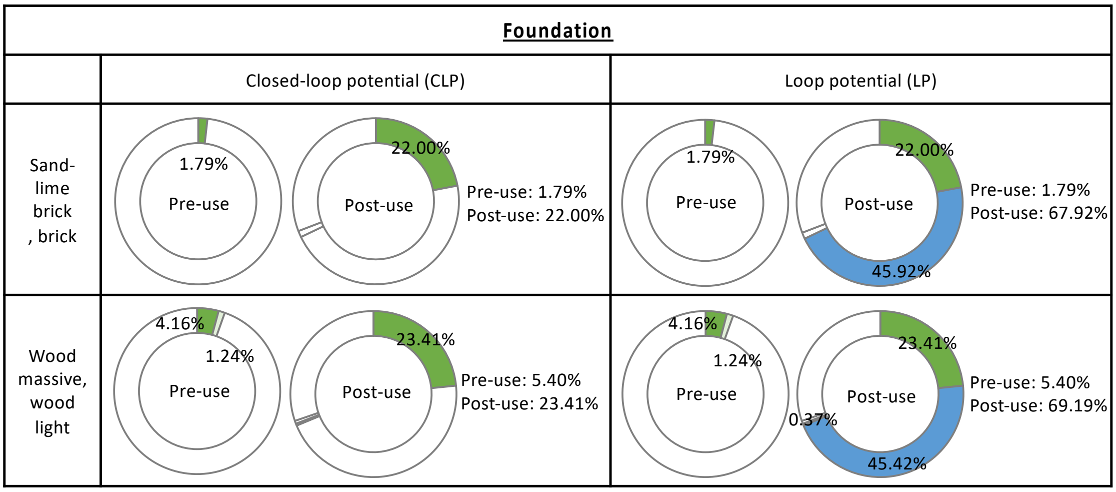


Figure 4-6: A schematic representation of the circularity potential results for the foundations of the four construction variants

The results of the circularity potential of the foundation under the four building construction variants are shown in Figure 4-6. Since the foundation structures under the sand-lime brick and the regular brick construction are the same, their circularity results are summarized in the same row in the figure. The circularity potential of the foundation under the massive and light wood construction is also combined in the same row in the figure.

In the pre-use phase, the CLP and LP of the foundation under the brick constructions are both 1.79%, while for the wood constructions, the CLP and LP are 5.40%. The reason for the low circularity potential performance of the four constructions is that the concrete and cement screed, which have the most significant mass share of the foundation, are currently made from 100% non-renewable primary materials. Wood fiber insulation, made from 100% renewable raw materials, and foam glass, made from 68% recycled materials, used in the foundation of the wood constructions result in slightly higher CLP and LP values than the foundation of the brick constructions.

In the post-use phase, the CLP of the foundation in the brick construction is 22%, with a LP of 67.92%, while the CLP of the foundation in the wood construction is 23.41%, with a LP of 69.19%. Approximately 46% of the materials in the foundation under the brick constructions will be downcycled, primarily associated with concrete and cement screed. Due to the extensive demolition work and limited MLP, only 21.6% of concrete will enter the high-grade EoL scenario, i.e., recycling. In comparison, 46% will enter into existing low-grade EoL scenario, i.e., downcycling. About 64% of the cement screed will be downcycled, and the remaining 36% will be disposed of.

External wall AW-01

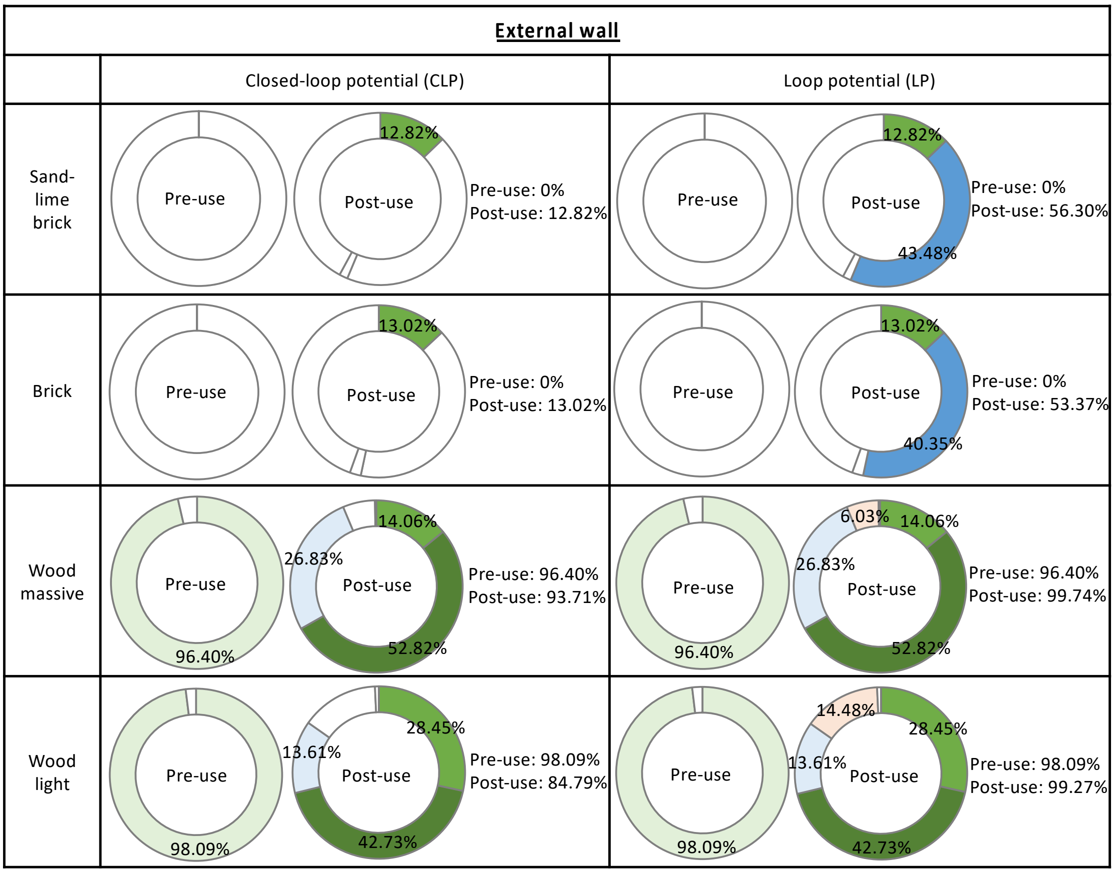


Figure 4-7: A schematic representation of the circularity potential results for the external walls of the four construction variants

Figure 4-7 shows a significant difference in the circularity potential between the brick and wood constructions in external walls, both for the pre-use and post-use phases. In the pre-use phase, the massive wood external wall has a CLP and LP value of 96.4%, while the light wood external wall reaches 98.09%, demonstrating very high circularity potential. All the materials used in massive and light wood external walls, except for the damp insulation layer, are made from at least 97% renewable primary resources.

In contrast, all the materials used in the external walls of the brick constructions are made entirely from non-renewable primary resources, showing 0% circularity potential.

In the post-use phase, sand-lime brick and regular brick external walls have similar circularity potential performance. The CLP of the sand-lime brick external walls is 12.82%, with a LP of 56.3%, meaning that 13% of the materials will enter closed-loop recycling, and 43% will enter downcycling. The most significant mass share of the external walls under the sand-lime brick construction is the sand-lime bricks, with approximately 17% recycled, 36% downcycled, and the remaining 47% disposed of. The regular brick external walls have a slightly lower LP of 53.37%, with 13% of the materials entering closed-loop recycling and 40% downcycling. The most significant portion of the mass share in the regular brick external walls is the brick, with 19% recycled, 28% downcycled, and 53% disposed of. The massive and light wood external walls exhibit similar circularity potential performance. The CLP of the massive and light wood external walls are 93.71% and 84.79%, respectively, with both having LP over 99%. Over 93% of the materials used in the massive wood external walls will enter closed-loop recycling, while over 84% of the materials used in the light wood external walls will enter closed-loop recycling. The load-bearing materials in the massive wood external walls, cross-laminated timber, can be entirely recycled in a closed loop. The most significant mass share in the light wood external walls, the wood fiber insulation, can be 70% recycled at the EoL.

Window FE-01

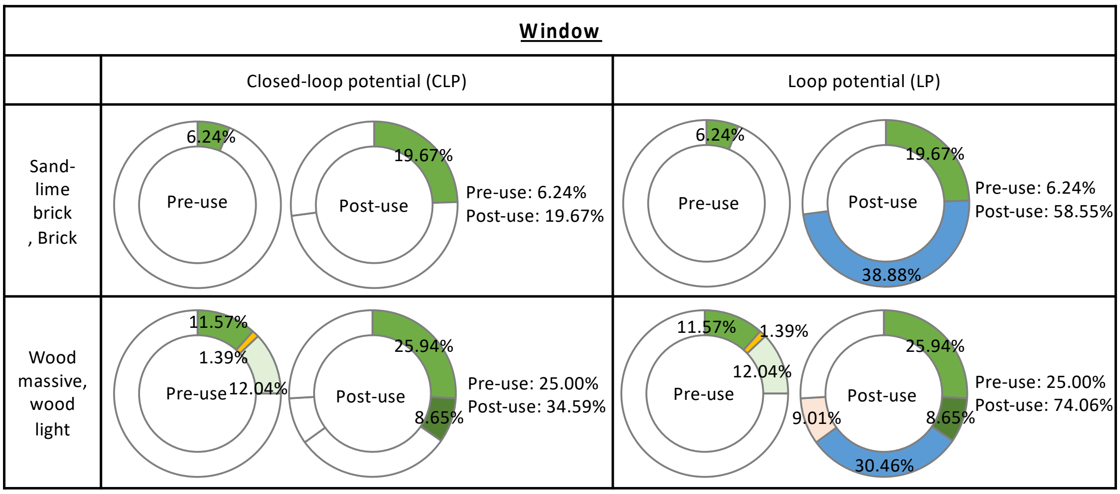


Figure 4-8: A schematic representation of the circularity potential results for the windows of the four construction variants

The circularity potential results of the windows under the four construction variants are shown in Figure 4-8. Since the window structures are the same in the sand-lime and the regular brick construction, their circularity potentials are summarized in the same row in the figure. The circularity potentials of the massive and light wood construction windows are also combined in the same row of the figure.

In the pre-use phase, the CLP and LP of the windows in the brick constructions are 6.24%, while the circularity potential of the windows in the wood constructions is higher than that of the brick constructions, reaching CLP and LP of 25%. The main reason for this difference is the use of PVC-U window frames and sashes in the brick constructions made from non-renewable raw materials. In the both wood and brick constructions, the largest mass share of the window is the triple-insulated glazing, consisting of approximately 90% non-renewable raw materials, resulting in their overall low circularity potential.

In the post-use phase, the CLP of the brick construction windows is 19.67%, and the LP is 58.55%, while the CLP of the wood construction windows is 34.59% and the LP is 74.06%. About 20% of the materials in the windows of the brick constructions will enter closed-loop recycling, and 39% will enter downcycling, while in the windows of the wood constructions, 35% of the materials will enter closed-loop recycling, and approximately 39% will enter downcycling. The triple-insulated glazing, which has the most significant impact on the circularity potential of the windows, will be 31.5% recycled, 37% downcycled, and the remaining 31.5% disposed of.

Internal wall IW-01

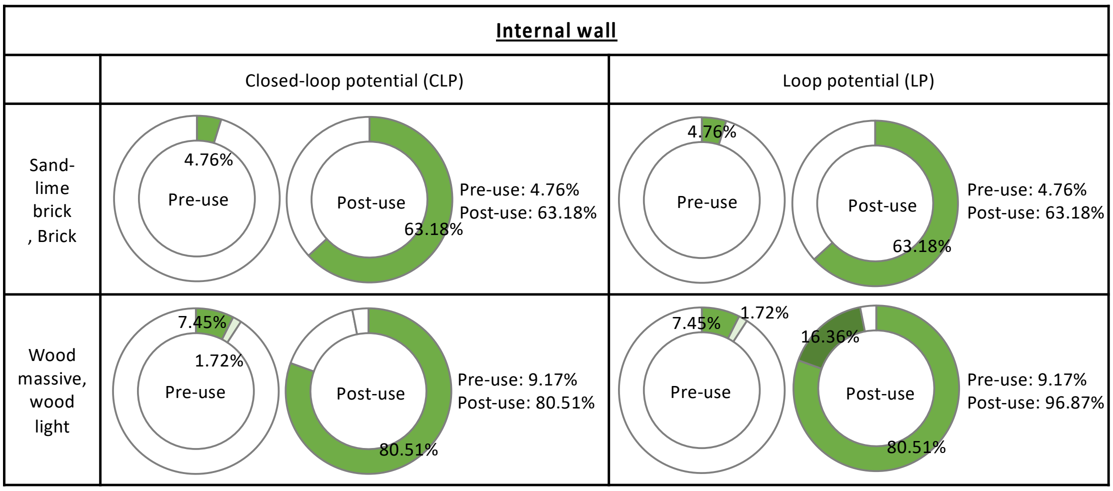


Figure 4-9: A schematic representation of the circularity potential results for the internal walls of the four construction variants

The circularity potential results of the internal walls under the four construction variants are shown in Figure 4-9. Since the internal wall structures are the same in the sand-lime and the regular brick constructions, their circularity potentials are summarized in the same row in the figure. The circularity potentials of the massive and light wood construction internal walls are also combined in the same row of the figure.

In the pre-use phase, the CLP and LP of the internal walls under the brick constructions are only 4.76%, while for the wood constructions, the CLP and LP are only 9.17%. From a structural perspective, the main difference between the brick and wood constructions lies in the internal wall panels. The double-layer gypsum boards are used in the internal walls of the brick constructions, while the wood constructions use clay panels. Both panels are made from over 97% non-renewable primary materials, resulting in a low circularity potential for the internal walls.

In the post-use phase, the internal walls of the brick constructions have CLP and LP of 63.18%, while for the wood constructions, the CLP is 80.51%, and the LP is 96.87%, indicating a higher circularity potential. 81% of the materials used in the internal walls of the wood constructions will enter closed-loop recycling, and 16% will enter open-loop recycling, with only a tiny portion being disposed of. In comparison, 63% of the materials used in the internal walls of the brick constructions will be recycled, with the remaining 37% being disposed of. The clay panels used in the internal walls of the wood constructions will be 81% recycled and 19% downcycled, while the gypsum boards used in the brick constructions will be 62% recycled, with the remaining 37% being disposed of.

Ceiling DE-01

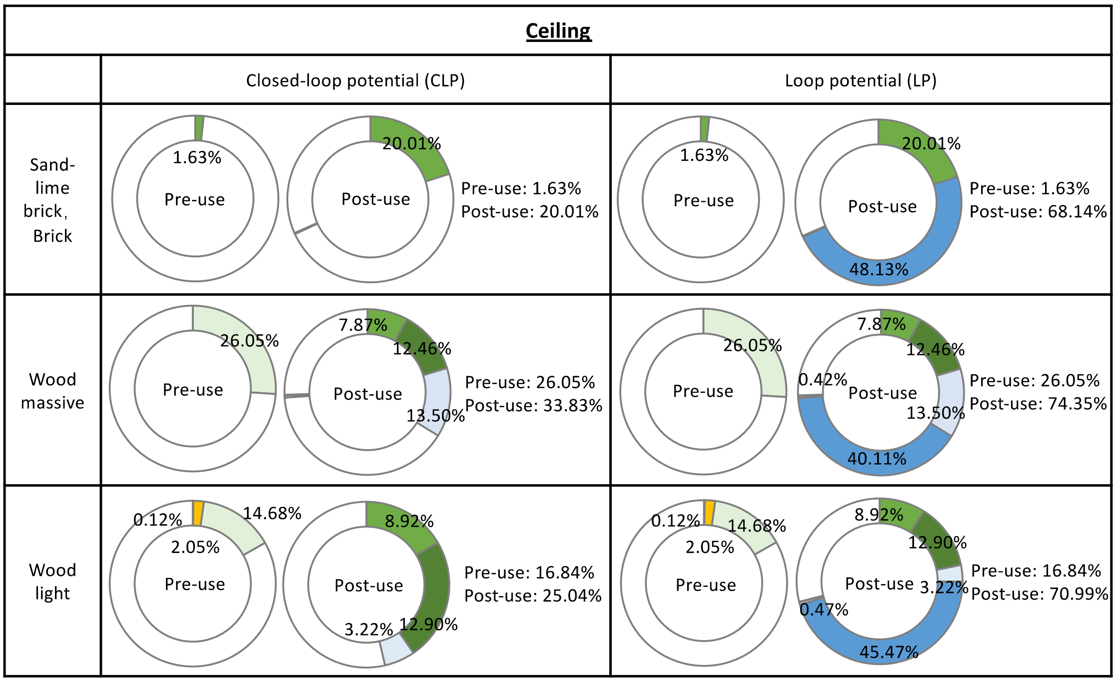


Figure 4-10: A schematic representation of the circularity potential results for the ceilings of the four construction variants

The circularity potential results of the ceilings under the four construction variants are shown in Figure 4-10. The ceiling structures are the same in the sand-lime and the regular brick construction, their circularity potentials are summarized in the same row in the figure.

In the pre-use phase, the CLP and LP of the ceilings in the brick constructions are 1.63%, while in the massive wood construction, the CLP and LP are 26.05%, and in the light wood construction, the CLP and LP are 16.84%. The extensive use of concrete and cement in the ceilings of the brick constructions contributes to the low circularity potential as they are made from 100% non-renewable primary materials. In contrast, in the wood constructions, the load-bearing concrete is replaced by cross-laminated timber, which comprises 95% renewable primary resources. However, using cement screed still results in a relatively low overall circularity potential in the wood constructions.

In the post-use phase, the CLP of the brick construction ceilings is 20.01%, and the LP is 68.14%, while in the massive wood construction, the CLP is 33.83%, and the LP is 74.35%, and in the light wood construction, the LCP is 25.04%, and the LP is 70.99%. 46% of the concrete and 64% of the cement used in the ceiling of the brick constructions will be downcycled, leading to 48% of the materials used in the ceiling entering open-loop recycling. The cross-laminated timber used in the ceilings of the wood constructions will be 100% recycled in a closed loop. More than 40% of the materials in the ceilings of the massive wood construction will be downcycled, and in the light wood construction, over 45% of the materials will be downcycled, with the most significant source being over 64% of the cement being downcycled.

Roof DA-01

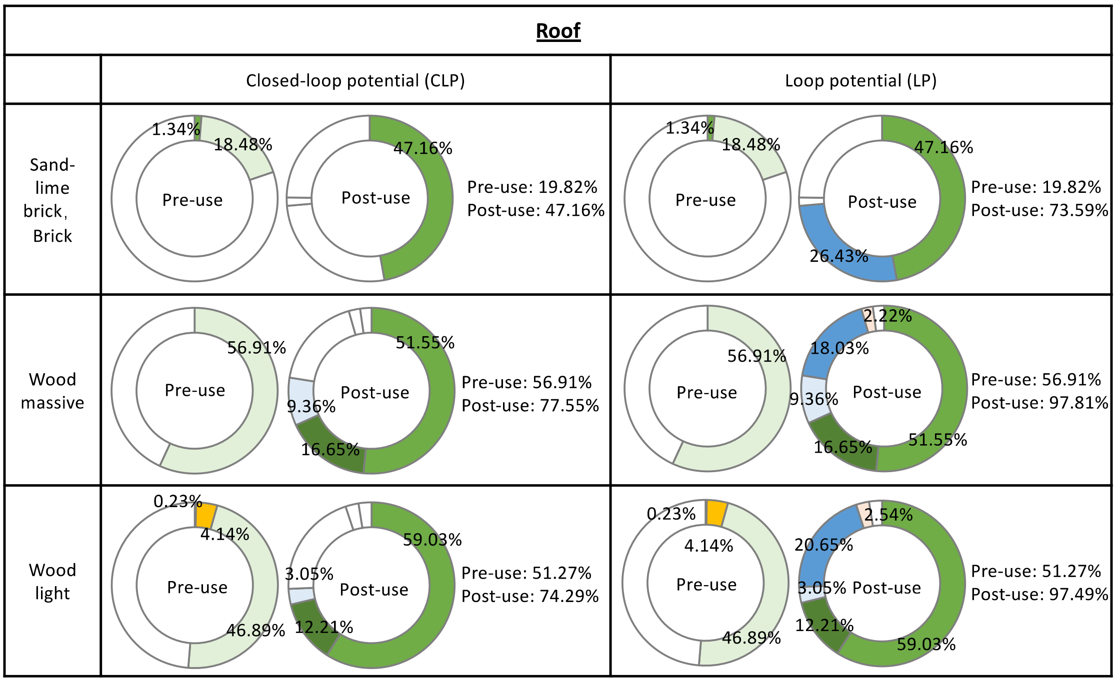


Figure 4-11: A schematic representation of the circularity potential results for the roofs of the four construction variants

The circularity potential results of the roofs under the four construction variants are shown in Figure 4-11. The roof structures are the same in the sand-lime and the regular brick construction, their circularity potentials are summarized in the same row in the figure. Since the MRC of the roof vegetation layer is not recorded in the Atlas Recycling, it is assumed in this calculation that the vegetation layer consists of 50% non-renewable primary resources and 50% renewable primary resources.

In the pre-use phase, the CLP and LP of the roofs under the brick construction are only 19.82%, while those of the wood construction roofs exceed 50%. Over 80% of the materials used in the roofs under the brick constructions come from non-renewable primary materials. In the massive wood construction roof, nearly 56% of the materials come from renewable primary resources, mainly from the vegetation layer and cross-laminated timber, while in the light wood roof, 46% of the renewable primary resources mainly come from the roof vegetation layers.

In the post-use phase, the circularity potential of the wood construction roofs is also higher than that of the roofs under the brick constructions. Over 47% of the materials used in the roofs of the brick constructions will enter closed-loop recycling, and 26% will enter downcycling, mainly from the vegetation layer and concrete. The roofs of the both wood constructions show high circularity potential, with CLP and LP of the massive wood roof reaching 77.55% and 97.81%, respectively, and those of the light wood roof reaching 74.29% and 97.49%, respectively. The vegetation layer, which contributes most to the circularity potential of the roofs, will be 72% recycled, with the remaining 28% being downcycled.

4.3. Results and Analysis of Correlation between Urban Mining Index and Global Warming Potential

4.3.1. Results on the Building Level

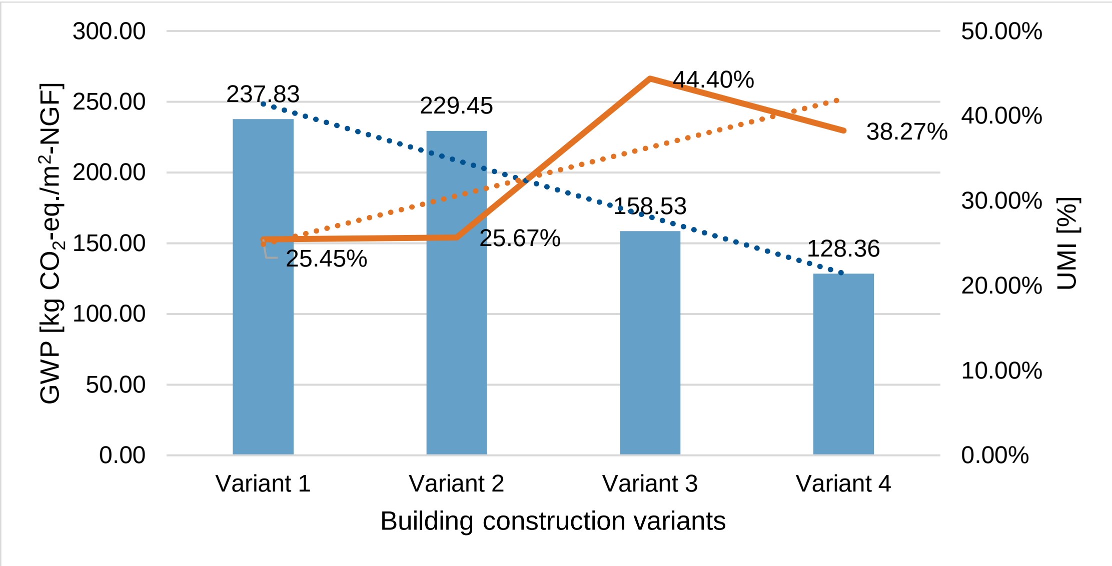


Figure 4-12: Combo diagram illustrating the variations of GWP and UMI in four building construction variants

Figure 4-12 illustrates the values and trends of GWP and UMI on the entire building level under different building construction variants in a combo diagram. Building under the brick constructions has a significantly higher GWP than those under the wood constructions, indicating a higher environmental load. The circularity potential of the building between the two brick constructions appears similar, with little difference in their UMI, both only have a UMI of 25%, suggesting an overall lower circularity potential. In comparison, buildings under the wood constructions show a marked advantage in GWP. Similarly, the circularity potential of the building under the wood constructions is significantly higher than that of the brick constructions.

It can be concluded that buildings under the brick constructions have higher GWP and exhibit lower circularity potential, while the buildings of the wood constructions have lower GWP and show higher circularity potential. Observing the two trend lines shows that as the blue trend line (representing GWP) gradually decreases, the orange trend line (representing UMI) shows an increasing trend, indicating that UMI increases as GWP decreases.

From the perspective of correlation coefficients, the Spearman correlation coefficient for the datasets is -0.8, with a p-value of 0.2, which indicates an insignificant strong negative correlation, meaning that as GWP values decrease, UMI shows an increasing trend. Scatter plots in the Figure 4-13 effectively illustrate this negative correlation. However, the calculated p-value is more significant than 0.05, indicating that the data is not statistically significant. One reason for this lack of significance is insufficient data. There are only four datasets on the building level, which results in a lack of statistical power according to statistical standards.

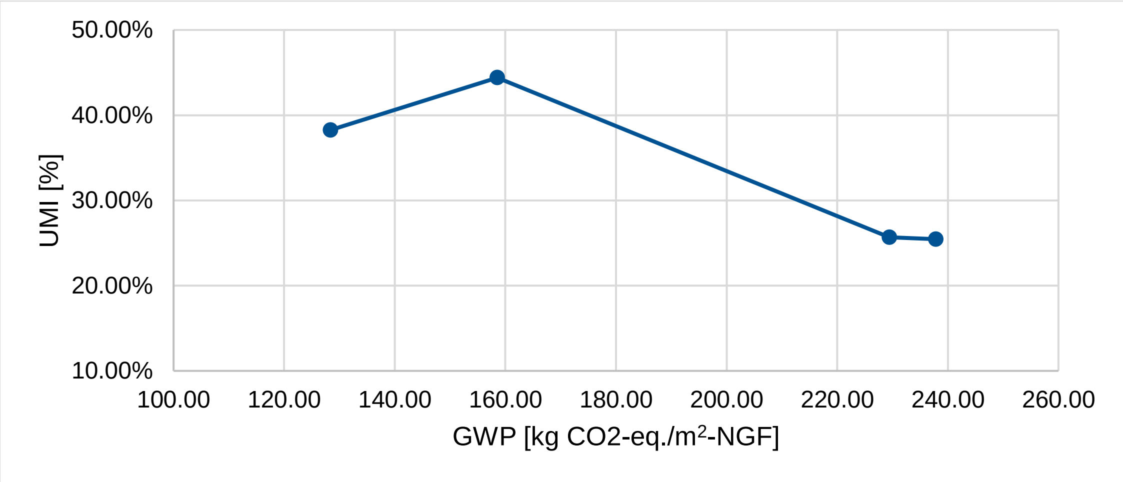


Figure 4-13: Scatter plots illustrating the correlation between GWP and UMI on the Building Level

4.3.2. Results on the Building Component Level

In the following section, GWP and UMI will be subject to correlation analysis on various levels of building components. The analysis will focus on the six building components across different construction variants, including foundations, external walls, windows, interior walls, ceilings, and roofs.

<u>Foundation G-01</u>

Figure 4-14 presents the values and trends of GWP and UMI for foundations across the four construction variants. The two brick constructions share the same foundation structure, and the two wood constructions have the same foundation structure, limiting the correlation analysis to only two datasets.

As shown in the figure, the foundation of the brick constructions has a higher GWP than that of the wood constructions, and its circularity potential is lower, only at

23.38%. In comparison, the GWP of the foundation under the wood constructions is 19% lower than that of the brick constructions, and its circularity potential is higher, with a difference of 2.5% in UMI.

From the perspective of the correlation coefficient, the Spearman correlation coefficient for the datasets is -0.94 with a P-value of 0.06, indicating a statistically insignificant strong negative correlation between GWP and UMI, suggesting that foundations with lower GWP tend to have higher circularity potential. However, this correlation should be interpreted cautiously due to the insufficient sample.

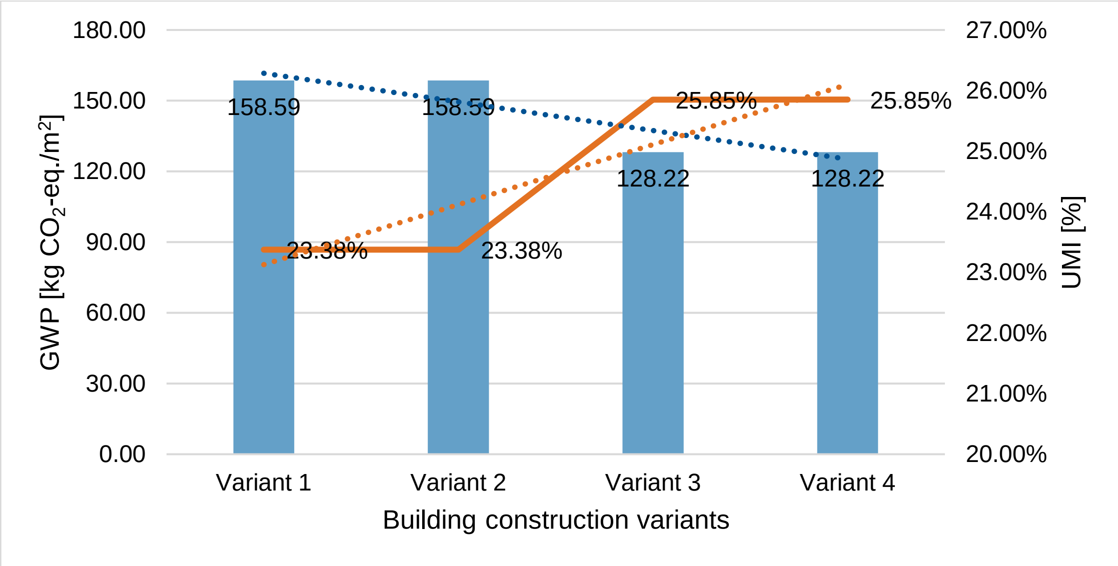


Figure 4-14: Combo diagram illustrating the variations of GWP and UMI for foundations under four building construction variants

<u>External wall AW-01</u>

As shown in the Figure 4-15, the GWP of the two brick construction external walls are relatively high. Specifically, the external wall of the sand-lime brick construction has the highest GWP, exceeding 100 [kg CO_2-eq./m^2], followed by the regular brick construction with 81.89 [kg CO_2-eq./m^2]. The circularity potential of the external wall of the two brick constructions is relatively low, at only 17%. In comparison, the two wood construction external walls have lower GWP and exhibit extremly high circularity potentials, with UMI exceeding 95%.

The two trend lines indicate that as the blue trend line (representing GWP) decreases, the red orange line (representing UMI) increases. The Spearman correlation coefficient for the datasets is -0.6 with a P-value of 0.4, indicating an insignificant strong negative correlation between GWP and UMI, suggesting that external walls with lower GWP tend to have a higher UMI.

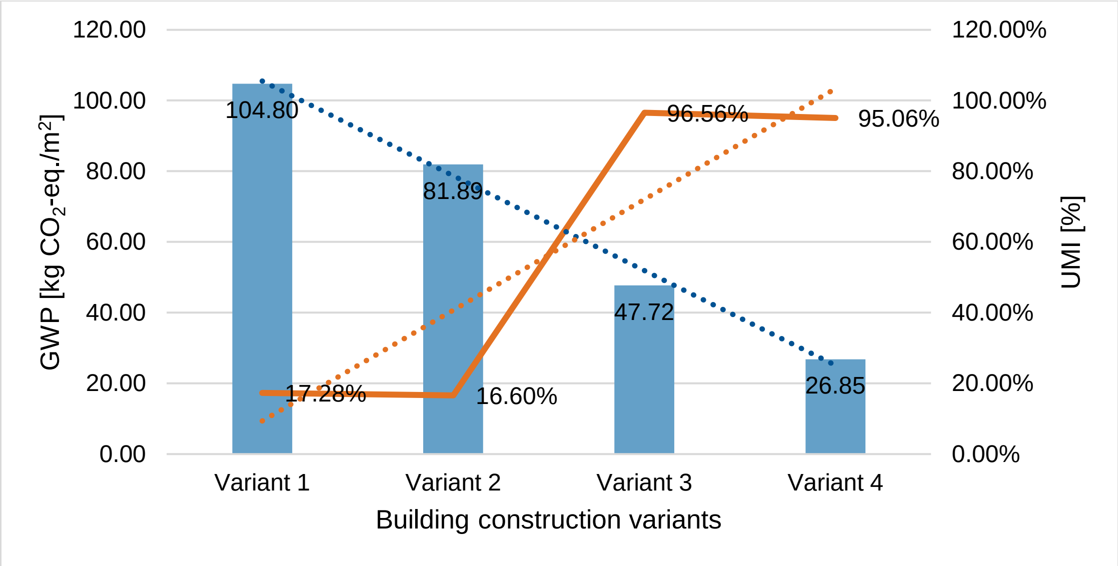


Figure 4-15: Combo diagram illustrating the variations of GWP and UMI for external walls under four building construction variants

<u>Window FE-01</u>

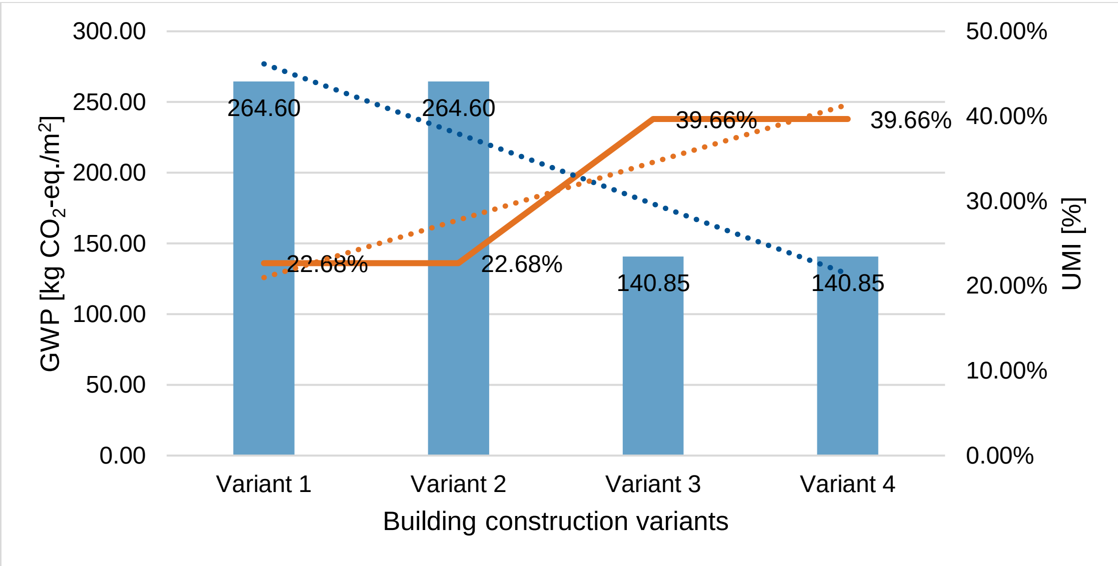


Figure 4-16: Combo diagram illustrating the variations of GWP and UMI for windows under four building construction variants

Figure 4-16 shows the values and trends of the GWP and UMI of windows under four construction variants. The dataset is limited to two groups because the window structures are the same between the two brick constructions and between the two wood constructions. The GWP of the window under the brick constructions is almost twice that of the wood constructions, reaching 264.60 [kg CO_2-eq./m^2]. The GWP of the PVC-U window sash and window frame used in the brick constructions is 3.3 times that of the wood constructions. Moreover, PVC-U window sash and frames made from 100% non-renewable materials, have only 42% of the materials entering open-loop recycling, showing a lower circularity potential. In contrast, windows under the wood constructions have lower GWP and higher circularity potential.

The Spearman correlation coefficient for these datasets is 1, with a P-value of 0, indicating a significant strong negative correlation, which suggests that windows with lower GWP tend to have a higher UMI. However, this correlation should be interpreted cautiously due to the insufficient sample.

Internal wall IW-01

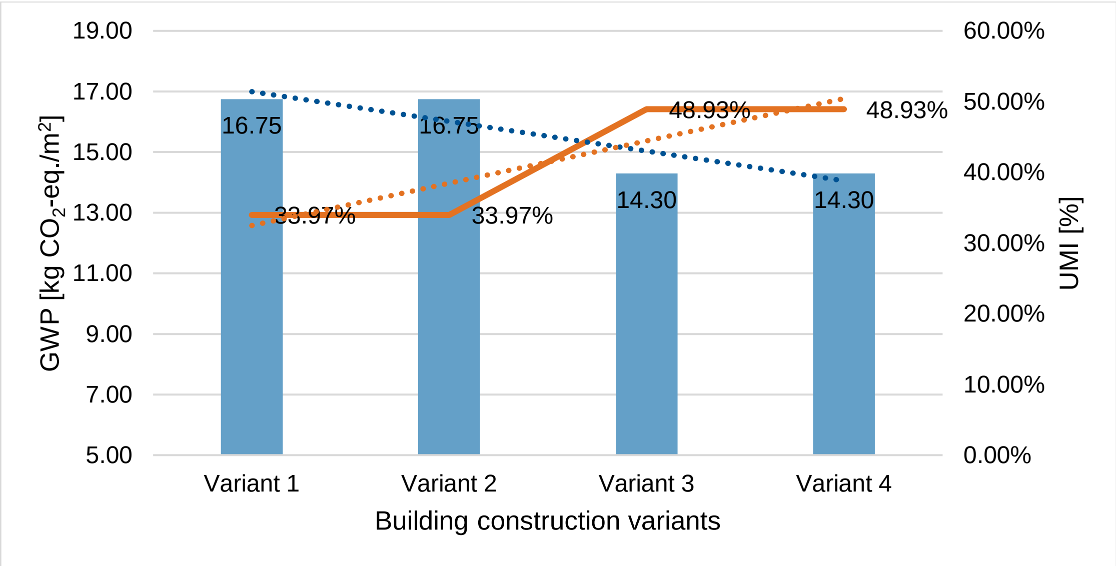


Figure 4-17: Combo diagram illustrating the variations of GWP and UMI for internal walls under four building construction variants

Figure 4-17 illustrates the values and trends of GWP and UMI of internal walls under the four construction variants. The correlation analysis of the internal wall is also based on two datasets. Overall, the brick construction internal walls have a higher GWP, reaching 16.75 [kg CO_2-eq./m^2], and a lower circularity potential, with a UMI of 33.97%. On the other hand, the wood construction walls have a GWP of 14.30 [kg CO_2-eq./m^2] and a UMI of 48.93%. This difference is primarily due to the use of different wall cladding materials. The GWP of the plasterboard used in the brick constructions is 18% higher than the clay panels used in the wood constructions, with a UMI of 32.19% for plasterboard and 46.25% for clay panels.

The Spearman correlation coefficient for the datasets is -0.94, with a P-value of 0.06, indicating an insignificant strong negative correlation, which implies that internal walls with lower GWP tend to have a higher UMI. However, the interpretation of the correlation should consider the limited sample size.

Ceiling DE-01

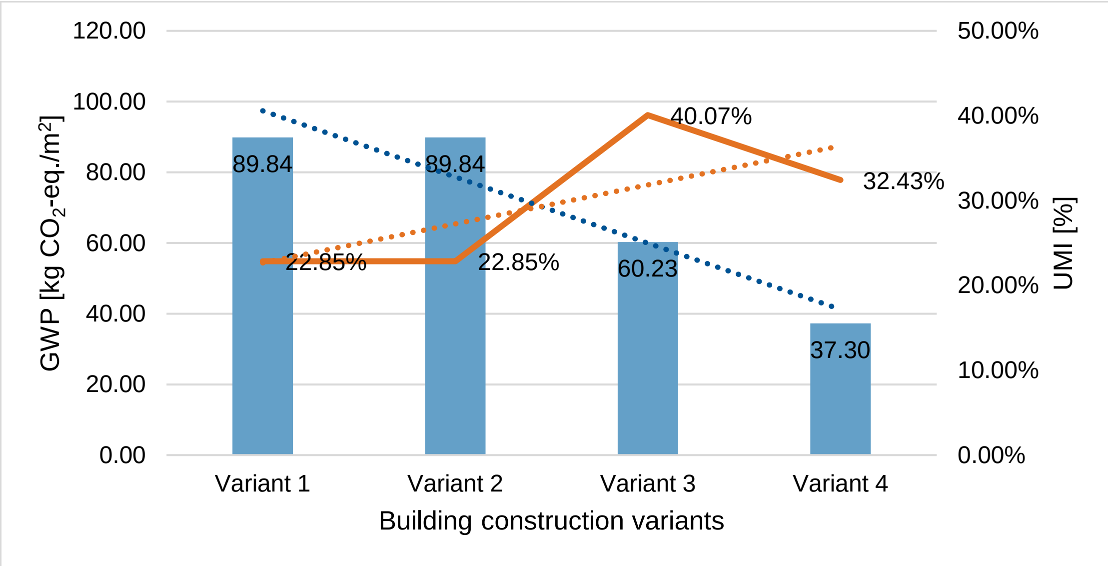


Figure 4-18: Combo diagram illustrating the variations of GWP and UMI for ceilings under four building construction variants

Figure 4-18 illustrates the values and trends of GWP and UMI of ceilings under different construction variants. This correlation analysis is based on three datasets. The GWP of the brick construction ceilings is relatively high, reaching 89.84 [kg CO_2-eq./m^2], and its circularity potential is low, with a UMI of 22.85%. In contrast, the ceilings under the wood constructions have lower GWP, with the massive wood construction at 60.23 [kg CO_2-eq./m^2] and light wood construction at 37.30 [kg CO_2-eq./m^2], and their circularity potential are higher, both exceeding 32%. The GWP of reinforced concrete used in the ceilings under the brick constructions is 26 [kg CO_2-eq./m^2] higher than the cross-laminated timber used in the massive wood construction and 53 [kg CO_2-eq./m^2] higher than the cross-laminated timber beam used in the light wood construction. Compared to the circularity potential of 97.5% for cross-laminated timber, the circularity potential of concrete is only 22.3%, and for steel, it is 67%.

The trend lines show that as the blue trend line (representing GWP) gradually decreases, the orange trend line (representing UMI) increases. The Spearman correlation coefficient for the datasets is -0.78, with a P-value of 0.22, indicating an insignificant strong negative correlation, suggesting that ceilings with lower GWP tend to have higher UMI.

The ceiling under the light wood construction performs better than the massive wood in terms of GWP. However, the circularity potential of the massive wood is higher than that of the light wood. There is no negative correlation between GWP and UMI when considering only the two wood-construction ceilings. A more detailed investigation of the reasons for these differences will be conducted in the discussion section of the next chapter.

Roof DA-01

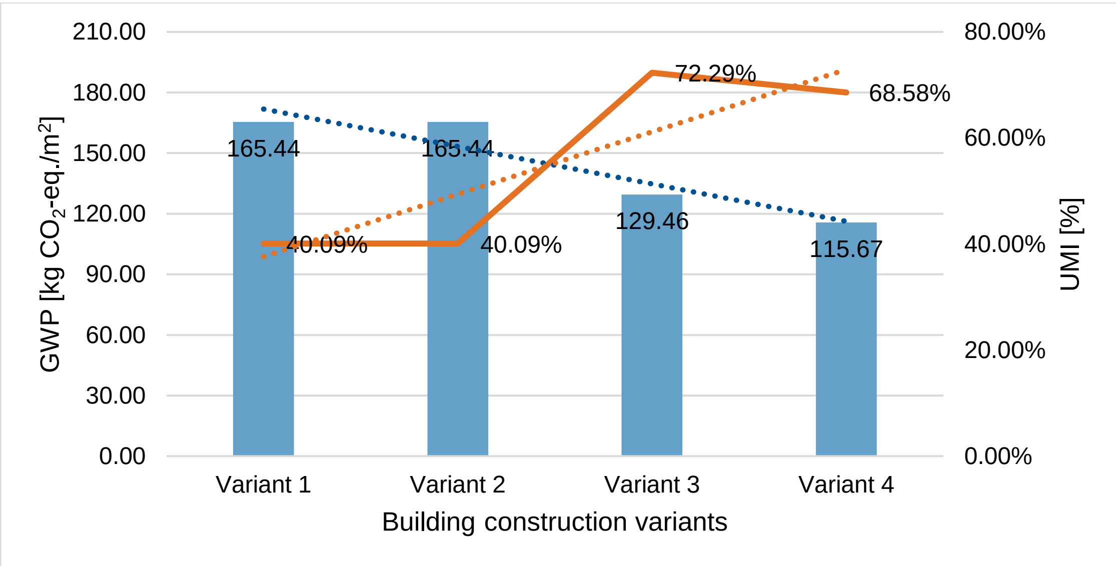


Figure 4-19: Combo diagram illustrating the variations of GWP and UMI for roofs in four building construction variants

Figure 4-19 represents the values and trends of GWP and UMI for roofs under different construction variants. The correlation analysis is based on three datasets. The GWP of the ceiling under the brick constructions is relatively high, reaching 165.44 [kg CO_2-eq./m^2], and it exhibits lower circularity potential, with a UMI of 40.09%. In comparison, the GWP of the ceiling under the two wood constructions is lower, below 130 [kg CO_2-eq./m^2], and their circularity potential is higher, with UMI exceeding 68%. The GWP of reinforced concrete used in the brick construction roof is

26 [kg CO_2-eq./m^2] higher than cross-laminated timber used in the massive wood roof and 40 [kg CO_2-eq./m^2] higher than cross-laminated timber beam used in the light wood roof. In terms of the circularity potential, the performance of reinforced concrete is much lower than the load-bearing materials used in the wood constructions.

The trend lines show that as the blue trend line (representing GWP) gradually decreases, the orange trend line (representing UMI) increases. The Spearman correlation coefficient for the datasets is -0.78, with a p-value of 0.22, indicating an insignificant strong negative correlation, suggesting that roofs with lower GWP tend to have a higher UMI. Similar to ceilings, when the study focuses on the two wood construction roofs, there is a lack of this negative correlation between GWP and UMI. This difference will be discussed in the discussion section.

<u>Conclusion on the building component level</u>

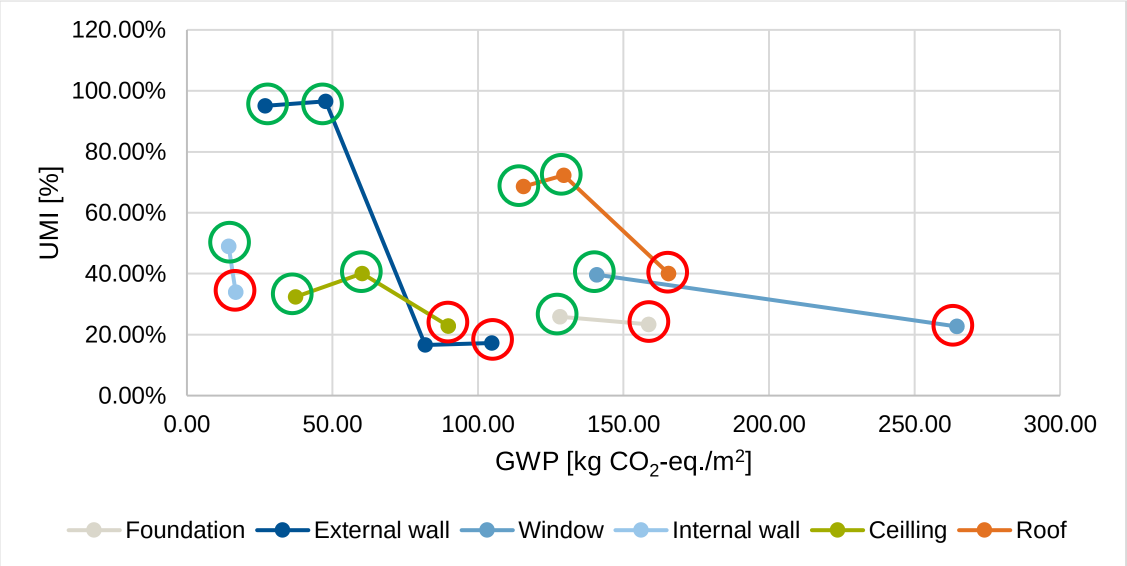


Figure 4-20: Scatter plots illustrating the correlation between GWP and UMI across six building components

Combining the analyses above and considering the correlation coefficients for all six building components, which range from -0.6 to -1.0, there is an insignificant strong negative correlation between GWP and UMI across all building components. To visually represent this result, GWP values are plotted on the x-axis, UMI values on the y-axis, and the numerical values of the building components mentioned above are summarized in the scatter plots, forming Figure 4-20.

By observing the six trend lines in the figure, it becomes clear that they all exhibit a downward trend as the GWP values on the x-axis increase. In other words, among these six trend lines, points with lower GWP values tend to have relatively higher UMI values, and points with higher GWP values have relatively lower UMI values. Designers prefer variants with lower GWP and higher UMI values for each building component. Therefore, points in the upper-left corner of the scatter plots, marked with green circles in the figure, are more environmentally favorable. In contrast, points in the lower-right corner, marked with red circles, should be avoided.

Further analysis reveals that among the six trend lines in the figure, points in the upper-left corner consistently belong to wood structures. In contrast, points in the lower-right corner are associated with brick structures. However, the light and massive wood construction each demonstrate their respective advantages regarding GWP and UMI in the ceilings and roofs. It is important to note that the negative correlation does not apply in this specific case.

4.3.3. Results on the Material Level

The following section will conduct a correlation analysis of GWP and UMI on building material levels. This analysis primarily focuses on three types of building materials, including load-bearing materials, insulation materials, and wall cladding materials.

<u>Load-bearing material</u>

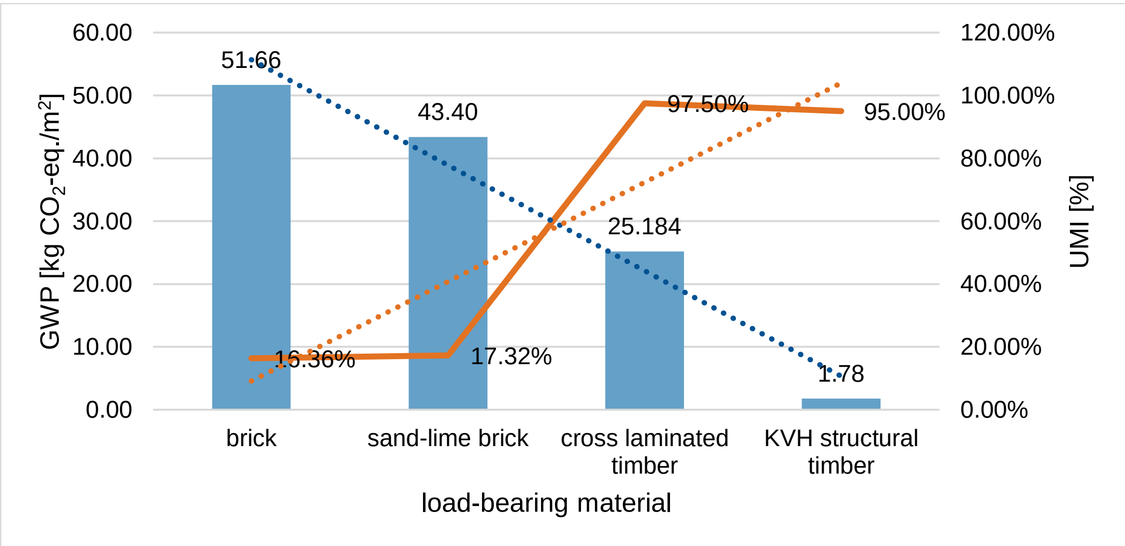


Figure 4-21: Combo chart illustrating GWP and UMI of different load-bearing materials on one square meter of wall

The values and trends of GWP and UMI for different load-bearing materials on one square meter of a wall are illustrated in Figure 4-21. Overall, there is a gradual decrease in GWP and an increase in UMI. The two load-bearing materials used in the brick constructions, regular bricks and sand-lime bricks, have higher GWP and lower UMI than load-bearing materials used in the wood constructions. While the GWP of sand-lime bricks is 8 [kg CO_2-eq./m^2] lower than that of the regular bricks, their UMI values show only a marginal difference, with a gap of only 1%, indicating that both materials have relatively low circularity potential. Similarly, the GWP of KVH structural timber used in the light wood construction is 23 [kg CO_2-eq./m^2] lower than cross-laminated timber used in the massive wood construction. However, both load-bearing materials exhibit incredibly high circularity potentials, exceeding 95%.

The trend lines show that as the blue trend line (representing GWP) gradually decreases, the orange trend line (representing UMI) increases. The Spearman correlation coefficient for this dataset is -0.8, with a p-value of 0.2, indicating an insignificant strong negative correlation between GWP and UMI. Load-bearing materials with higher GWP tend to have lower circularity potential, while load-bearing materials with lower GWP values often have higher circularity potential. However, this negative correlation is not evident within load-bearing materials used in the wood constructions.

Insulation material

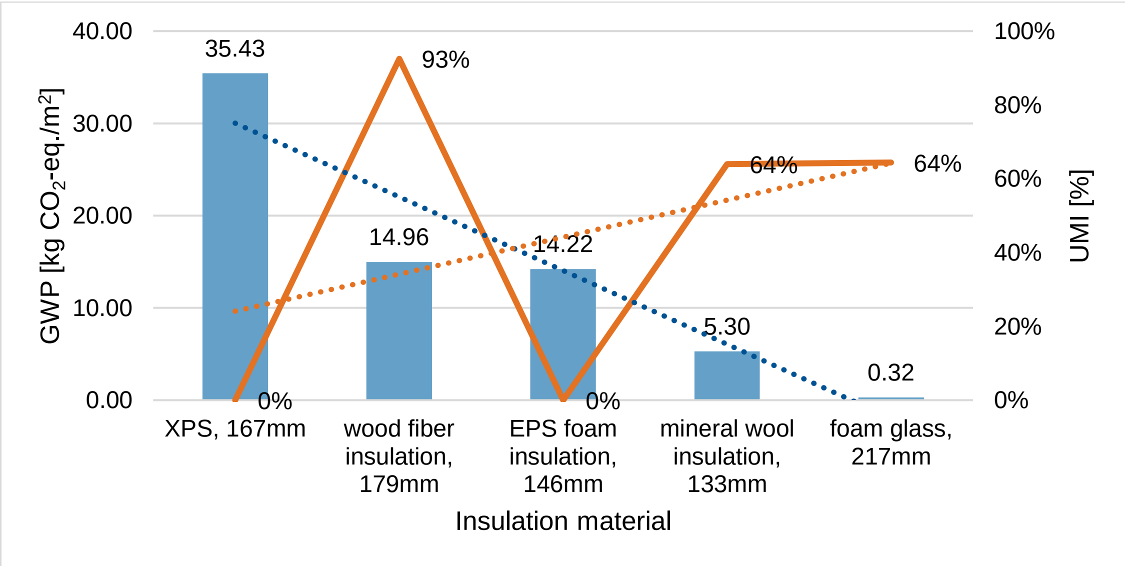


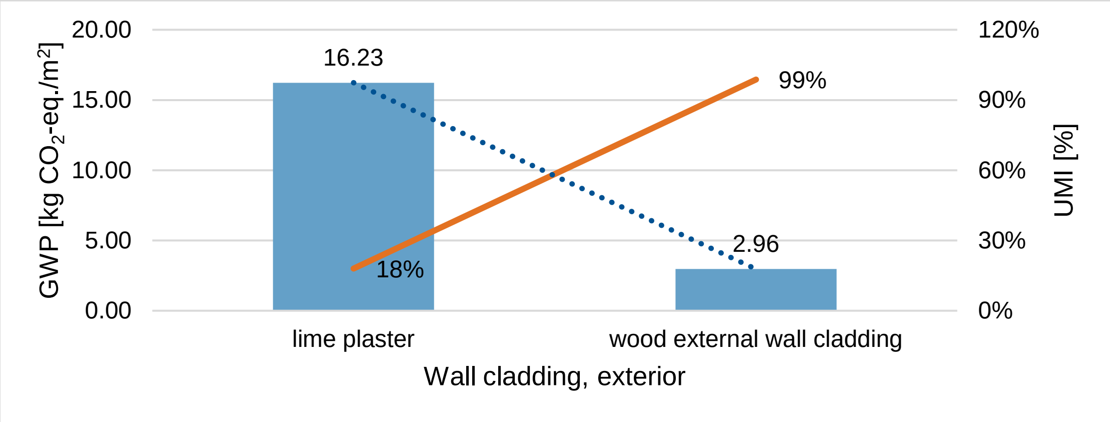
Figure 4-22: Combo chart illustrating GWP and UMI of different insulation materials on one square meter of wall

Figure 4-22 presents the combo chart illustrating the performance of different insulation materials on GWP and UMI per square meter of wall. It is important to note that the thickness of each insulation material must be calculated separately to ensure the same insulation effect for each square meter of external wall. In this context, achieving the same insulation effect means that the insulation material must ensure a U-value of 0.24 [W/(m^2·K)] for the external wall.

XPS has the highest GWP of 35.43 [kg CO_2-eq./m^2] among the five insulation materials, and it does not have circularity potential, with a UMI of 0%. Additionally, the two insulation materials with the lowest GWP, mineral wool and foam glass, have higher circularity potentials, reaching 64%. The required thickness of mineral wool is 39% less than that of foam glass per square meter of the external wall to achieve the same insulation effect. Insulation materials with similar GWP of 14 [kg CO_2-eq./m^2], wood fiber and EPS, exhibit significant differences in circularity potential. Wood fiber has the highest circularity potential among the five insulation materials, reaching 93%, while EPS has no circularity potential, with a UMI of 0%. Both XPS and EPS exhibit relatively higher GWP and lower circularity potential as fossil materials, while bio-based wood fiber insulation has high GWP and circularity potential. In contrast, mineral wool and foam glass show lower GWP values and higher circularity potential.

The trend lines show that as the blue trend line (representing GWP) gradually decreases, the orange trend line (representing UMI) increases. The Spearman correlation coefficient for the dataset is -0.3, with a p-value of 0.6, indicating an insignificant weak negative correlation between GWP and UMI. In general, regarding insulation materials of fossil and mineral origin, materials with higher GWP values tend to have lower circularity potential, materials with lower GWP values typically have higher circularity potential. However, this negative correlation does not exist in wood fiber insulation.

Wall cladding material



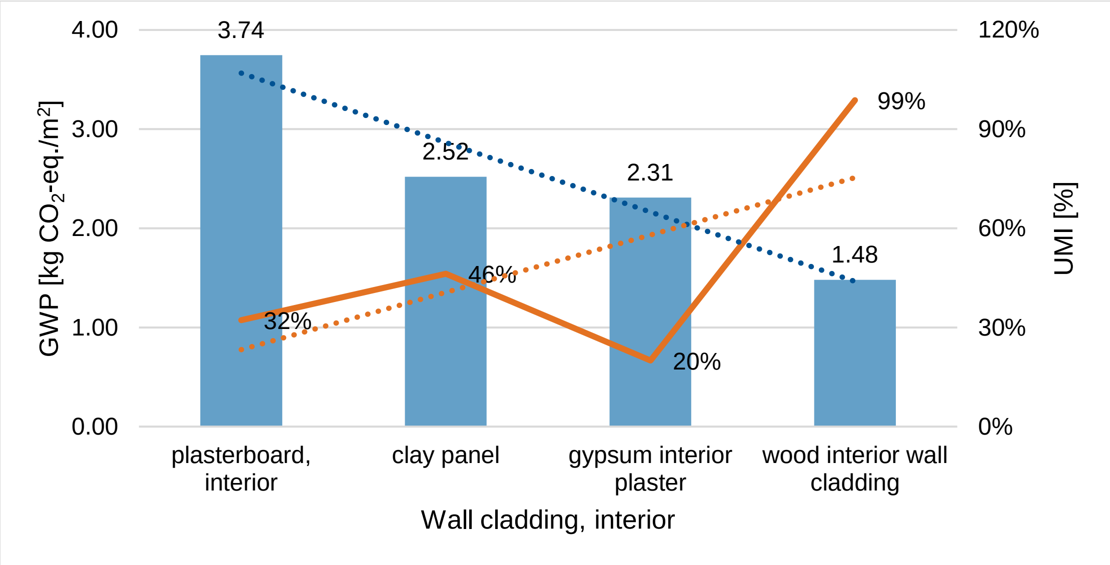


Figure 4-23: Combo chart illustrating GWP and UMI of wall exterior and interior cladding materials on one square meter of wall

Figure 4-23 consists of combo charts illustrating the GWP and UMI per square meter of wall area for two wall exterior cladding materials and four wall interior cladding materials. Regarding wall exterior cladding materials, compared to lime plaster, wood cladding material has a significantly lower GWP of 2.96 [kg CO_2-eq./m^2] and simultaneously possesses a remarkably high circularity potential, reaching 99%. Plasterboard shows the highest GWP of 3.74 [kg CO_2-eq./m^2] and relatively lower circularity potential among the four wall interior cladding materials, with a UMI of 32%, while wood interior cladding has the lowest GWP of 1.48 [kg CO_2-eq./m^2], and the highest circularity potential, with a UMI of 99%. There is little difference between gypsum interior plaster and clay panel regarding GWP. However, clay panel surpasses gypsum interior plaster in circularity potential, with a 26% difference in their UMI values. The circularity potential of gypsum interior plaster is the lowest, with a UMI of only 20%.

The trend lines show that as the blue trend line (representing GWP) gradually decreases, the orange trend line (representing UMI) increases. A gradual decrease in GWP values is associated with an upward trend in UMI for both wall exterior and interior cladding. Regarding the four wall interior cladding materials, the Spearman correlation coefficient is -0.4, with a p-value of 0.6, indicating an insignificant weak negative correlation between GWP and UMI. The conclusion is that wall cladding materials with lower GWP values, whether for exterior or interior use, tend to have higher recycling potential.

Conclusion on the material level

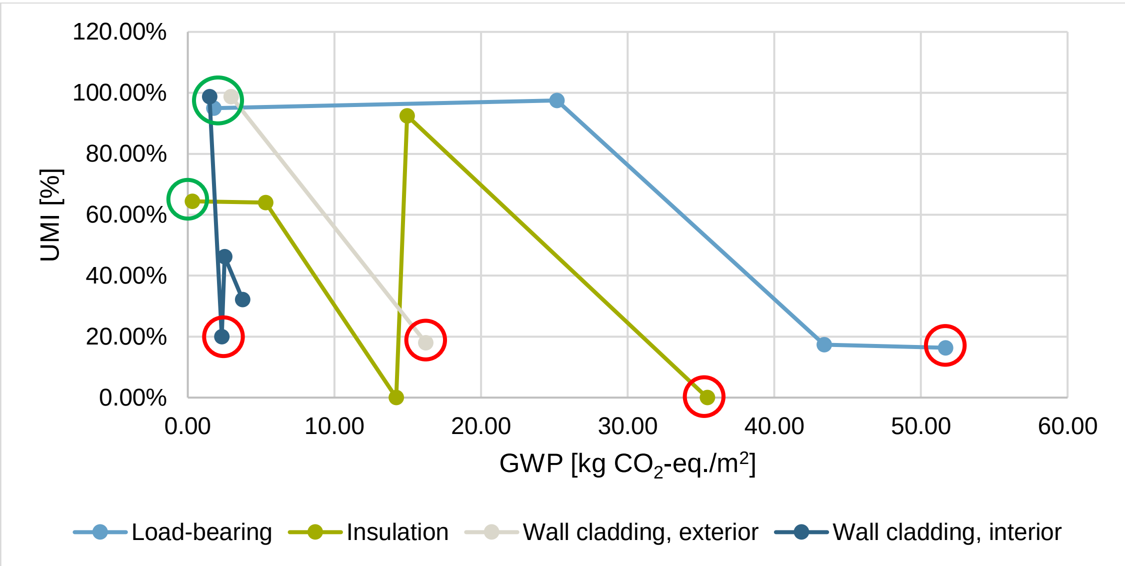


Figure 4-24: Scatter plots illustrating the correlation between GWP and UMI across four types of building materials

Regarding building materials, we have obtained three correlation coefficients, with one reaching -0.8, indicating a strong negative correlation, one reaching -0.3, and one reaching -0.4, indicating a weak negative correlation. By placing GWP values on the x-axis and UMI values on the y-axis, the numerical values of the above building materials are comprehensively summarized in Figure 4-24 with scatter plots.

As GWP values on the x-axis increase, a general downward trend in the four line segments can be observed in the figure, representing a gradual decrease in UMI values. Regarding insulation materials, a noticeable outlier in the line segments corresponds to the wood fiber insulation. Due to its bio-based character, it exhibits both high GWP and extremely high circularity potential.

Overall, among these four types of building materials, the point with the highest GWP on the x-axis generally has a lower UMI than other points. Furthermore, it is observed that points with the lowest GWP values tend to cluster in the upper-left area of the chart, representing that those points tend to have higher circularity potential. Materials that designers should prioritize to be chosen are located in this area, as they have lower GWP and higher circularity potential. Building materials in the upper-left corner include KVH structural timber, foam glass, wood external wall cladding, and wood interior wall cladding. Among these, three are bio-materials, and one is a mineral material. Conversely, building materials in the lower-right area of the chart, marked with red circles, are ones designers should aim to avoid, including brick, XPS, lime plaster, and plasterboard. Among these, three are mineral materials, and one is fossil material.

5. Discussion

5.1. Summary of Findings

5.1.1. Findings from Life Cycle Assessment

This study adopts a modified modeling method to analyze the GWP generated by six building components within their lifecycle in four construction variants. The key findings derived from this LCA analysis are as follows:

- The two wood constructions are superior to the two brick constructions, as evidenced by the total GWP of the building under the two brick constructions, which is approximately 1.5 times higher than that under the massive wood construction, and 1.8 times higher than that under the light wood construction.

- There is almost no significant difference in the total GWP of the building under the regular brick and the sand-lime brick construction, with the regular brick being slightly better than the sand-lime brick construction. Their structural differences mainly exist in the external wall, with other building components having the same structures.

- The GWP of external walls under the regular brick construction is 22% lower than that under the sand-lime brick construction.

- The two materials contributing the most to the GWP of the external wall under the sand-lime brick construction are EPS insulation and sand-lime bricks, each accounting for 41% of the GWP of the external wall.

- The material contributing the most to the GWP of the external wall under the regular brick construction is bricks, accounting for 63% of the GWP of the external wall.

- The light wood construction is superior to the massive wood construction. The total GWP of the building under the massive wood construction is 24% higher than that under the light wood construction.

- The volume of wood used in ceiling and roof under the massive wood construction is much greater than under the light wood construction, resulting in a lower GWP of these two building components in the light wood construction.

- The production stage contributes the most to the total GWP under the two brick constructions, with the production stage of the sand-lime brick construction accounting for 70% of the total GWP and the production stage representing 74% of the total GWP in the regular brick construction.

- The EoL stage contributes the most to the total GWP under the two wood constructions.

- Building under the massive wood construction contains more wood than those under the light wood construction. Consequently, the massive wood construction can store more carbon during the production stage, and at the same time, it will release more carbon during the EoL stage.

- Whether in the brick constructions or wood constructions, ceilings are the building component that contributes the most to the total GWP. Ceilings account for 32% of the total GWP in the sand-lime brick construction, 33% in the regular brick construction, 32% in the massive wood construction, and 25% in the light wood construction.

- Replacing reinforced concrete with wood in ceilings is beneficial for achieving a lower GWP. The GWP of the ceiling under the massive wood construction is 33% lower than under the brick constructions, while the GWP of the ceiling under the light wood construction is 58% lower than under the brick constructions.

5.1.2. Findings from Urban Mining Index Analysis

This study analyzed the circularity potential of buildings, building components, and materials across four building construction variants by calculating the mass share of circular materials before and after the use phase of the building throughout the entire life cycle. The key findings are as follows:

- On the building level, the overall circularity potential of the buildings under the wood construction variants is higher than that under the brick construction.

Among the four variants, the massive wood construction variant has the highest UMI, while sand-lime brick has the lowest UMI, with a difference of 18.9%.

- On the building level, the circularity potential of the ceiling significantly influences the building's overall circularity potential, while windows have the most negligible impact. Since the circularity potential of the whole building is derived from the sum of the product of each building component's weighted circularity potential and its mass share, the components with the highest mass share of the building contribute significantly. Ceilings have the highest mass share among the four construction variants, while windows have the lowest.
- The UMI of buildings under the sand-lime brick and brick construction variants is nearly the same, with the difference arising from load-bearing materials used in the external walls. Sand-lime bricks and bricks do not have circularity potential in the pre-use phase. However, sand-lime bricks have a higher circularity potential in the post-use phase than regular bricks. 16.64% of lime bricks will be recycled, 36% will be downcycled, while 18.72% of regular bricks will be recycled, and 28% will be downcycled.
- The circularity potential of the building under the massive wood construction variant is higher than that of the light wood construction variant, with the notable disparity primarily evident in the circularity potential of external walls, ceilings, and roofs. Among these three building components, the circularity potential under the massive wood construction is higher than that under the light wood construction, with the ceiling showing the most significant difference, a 7.7% gap in UMI.
- The difference in foundation structure between the brick and wood construction variants lies in insulation materials, resulting in distinct circularity potentials. The two insulation materials used in the foundation of the brick constructions, EPS and XPS, have no circularity potential. In contrast, the two insulation materials used in the foundation of the wood constructions, wood fiber and foam glass, exhibit higher circularity potentials, with wood fiber reaching 92.5% and foam glass reaching 64.4%.

- The circularity potential of building external walls is lowest under the regular brick construction at 16.60% and highest under the massive wood construction at 96.56%.

- The circularity potential of windows is higher under the wood construction variant than the brick construction, with a notable difference of 17%, mainly due to different materials used in window sashes and frames. Under the brick construction, 100% of the PVC-U is composed of non-renewable resources, with 42% entering a downcycling loop and the remaining 58% incinerated. In wood construction, only 5% of materials come from non-renewable resources, with 49% entering a closed-loop and the remaining 51% entering an open-loop recycling.

- The circularity potential of the internal wall under the wood constructions is higher than that of brick constructions, with a difference of 15%, stemming from using different wall cladding materials. Although both plasterboard and clay panels comprise over 97% non-renewable resources, the circularity potential of clay panels is significantly higher than that of plasterboard in the post-use phase. 81% of clay panels will enter closed-loop recycling, while the remaining 19% will be downcycled.

- Among ceilings, the massive wood construction variant has a higher circularity potential than the other three. The ceiling under the brick construction variant displays shallow circularity potential in the pre-use phase, with 98% of materials coming from non-renewable resources. In contrast, the ceiling of the massive wood construction has a non-renewable resource composition of 74%, and the light wood variant is 83%. In the post-use stage, 20% of the materials used in the ceiling of the brick variant will enter closed-loop recycling, 48% will be downcycled; for the massive wood variant, 34% will enter closed-loop recycling, 41% will enter open-loop recycling; and for the light wood variant, 25% will enter closed-loop recycling, 46% will enter open-loop recycling.

- Roofs under the two wood construction variants have a much higher circularity potential than those under the brick construction. In the brick variant, 80% of roof materials come from non-renewable resources, while both wood construction variants have a composition of non-renewable resources below 50%. In the post-use phase, 47% of materials used in the roof of the brick variants will be recycled, 26% downcycled, and 27% disposed of. Materials used in the roofs of the two wood construction variants will enter different quality levels of circular loops, with no materials being disposed of.

5.1.3. Findings from the Correlation Analysis

The analysis of GWP and UMI primarily focuses on the building level, building component level, and building material level. The key conclusions derived from the analysis are as follows:

- On the building level, GWP and UMI exhibit an insignificant strong negative correlation. The total GWP of buildings under the wooden construction variants is lower than the brick construction variants, with higher UMI.

- On the building level, the negative correlation is not evident within the two wood construction variants. Building under the light wood construction variant has a lower GWP than the massive wood variant, but its circularity potential is also lower.

- On the building component level, GWP and UMI show an insignificant strong negative correlation across six building components. Building construction variants with lower GWP in each building component tend to have higher circularity potential.

- Within wall load-bearing materials, GWP and UMI exhibit an insignificant strong negative correlation. Two load-bearing materials used in the wooden constructions, cross-laminated timber and KVH structural timber, have lower GWP values and higher circularity potential, exceeding 95%, compared to sand-lime brick and regular brick.

- Among the five building insulation materials, GWP and UMI demonstrate an insignificant weak negative correlation. Building insulation materials with lower GWP values tend to have higher circularity potential, except wood fiber insulation, which shows high GWP and a remarkable circularity potential of 93%.

- Regarding wall cladding materials, GWP and UMI exhibit an insignificant weak negative correlation for wall interior cladding material. Wall cladding materials with lower GWP values tend to have higher circularity potential.

- On the building material level, Bio-materials are recommended for use in load-bearing and wall cladding materials. Mineral materials are recommended for insulation due to their lower GWP and higher circularity potential. Fossil materials, characterized by high GWP and extremely low circularity potential, are not recommended.

5.2. Limitations of the Study and Recommendations

5.2.1. Limitation of the Life Cycle Assessment and Recommendations

This study conducted a LCA analysis to evaluate the GWP of four building construction variants for the research project ECO+. It is worth noting that this study used a modified modeling method, integrating existing recycling modeling methods and considering the future recycling rate of the building materials in the post-use phase into the LCA analysis. Also, this study has some limitations.

Firstly, the study has certain limitations in the system boundaries. As in the early design phase of the project, the carbon emissions associated with transportation, construction, use, and demolition were not considered. Based on the LCA and circularity potential analysis, wood construction variants are superior to brick constructions in terms of both GWP and UMI. However, the scope of this study was limited to embodied carbon emissions, with the carbon emissions generated during the operational phase of the building being overlooked. Bricks, as a high-density material with high mass, can absorb more heat during the daytime and release it at night than wood, which is beneficial in stabilizing indoor temperatures and thus reducing the energy requirements for heating or cooling. Integrating operational carbon emissions with building energy simulation tools into LCA analysis is needed for a more comprehensive simulation of the carbon emissions throughout its entire lifecycle, enabling a more accurate analysis of the correlation of GWP and UMI.

Secondly, the modified modeling method used in the study has certain limitations. The modeling of recycling in LCA can be divided into two parts: the input of recycled materials in the pre-use phase and the output of recycled materials in the post-use phase.

Equation 3 used in this study for the recycling modeling only includes the modification for the latter. The reason is that, as mentioned in section 3.3.4, in the Ökobaudat database, the input of recycled materials is considered in stages A1-A3, but the percentage is unknown. Consequently, based on Equation (3), it is difficult to accurately assess the impact of changing the input of recycled materials on the total carbon emissions. In this case, it is necessary to analyze at a theoretical level by focusing on the modeling method of Ökobaudat. As shown in Figure 3-7, for building materials that show a negative impact on the environment during lifecycle stages A1-A3 ($E_{A1-A3} > 0$), such as mineral materials, metal materials, and fossil materials, increasing the percentage of recycled material input produce lower carbon emissions as long as the load generated during the recycling process of input materials is smaller than the load generated during the production of virgin materials. For biomass materials such as wood, the Ökobaudat database considers the carbon storage during the growth of trees, i.e., the portion of biomass carbon storage. Additionally, EN16485:2014 specifies that the input of recycled wood should include the portion of biomass carbon storage. The same conclusion can be drawn for biomass materials, as long as the load generated during the recycling process of input is smaller than the load generated during the production of raw materials, increasing the percentage of recycled material input is advantageous for lower carbon emissions. There is a need to develop such a method and a corresponding database that can effectively demonstrate the benefits of increasing the recycled inputs of all types of materials while also individually modeling the carbon emissions generated by the materials produced from virgin or recycled materials.

In the post-use phase, it is evident from equation 3 that for mineral materials, metal materials, and fossil materials, as long as the emissions related to material recycling processes in lifecycle stage C3 are lower than the emissions generated from material disposal ($E_{C3} < E_{C4}$), increasing the output of recycled materials leads to lower carbon emissions. The existing processing method for biomass materials is burning at the EoL stage. If material recovery is conducted instead of 100% incineration, the allocation of carbon storage becomes an issue. Equation (3) cannot answer the impact of changing recycling rate on carbon emissions for biomass materials in situations where part of the materials is incinerated, and part is recycled (material recovery). More research is needed to simulate the carbon emissions associated with the material recovery of wood products separately. On the other hand, database Ökobaudat only has a single simulation of the EoL stage for most of the materials. For example, the GWP of concrete used in the foundation obtained from Ökobaudat is based on concrete used as

100% backfill materials (e.g., in road construction) in the post-use phase. However, through the circularity potential analysis in this paper, it is found that 21.6% of concrete can be recycled after use, 46% can be downcycled, and the remaining 32.4% will be disposed of. The modified modeling method used in this paper only considered the data of the C3 phase in the Ökobaudat. Consequently, there is a certain gap between the GWP calculated and the actual carbon emissions generated by the materials in reality (see Figure 5-1). Ökobaudat and Atlas Recycling have employed different modeling methods to assess the recycling content of materials in the pre-use phase and their recycling rates in the post-use phase, revealing a lack of uniformity in the data across these two databases. This highlights the need for developing a unified scientific database that records materials' current and potential recycling rates. Moreover, future efforts should focus on developing methods to independently simulate the recycling of building materials throughout their whole life cycle at different quality levels, which would help designers determine the carbon emissions of a product based on the materials' actual recycling rate.

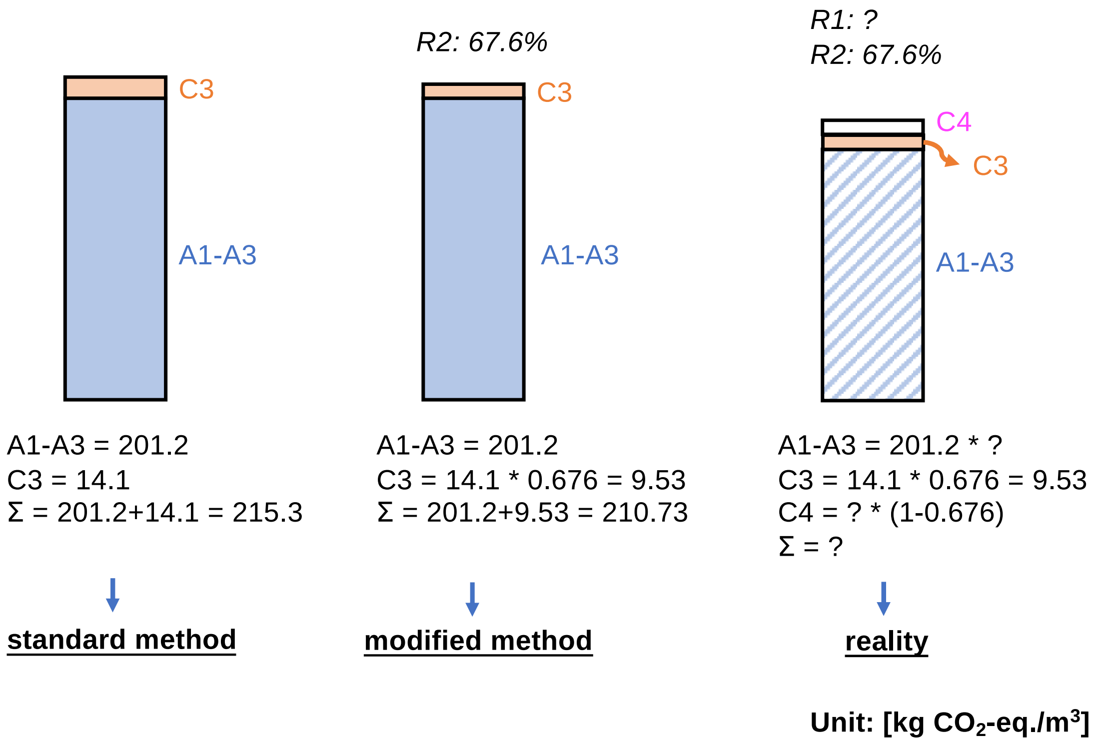


Figure 5-1: Schematic representation of the gap between modeled and actual carbon emissions of one cubic meter concrete

Figure 5-2 illustrates the total carbon emissions of 1000 kg sand-lime bricks calculated using standard and modified methods proposed in this study. The Ökobaudat database provides two scenarios for the EoL stage of sand-lime bricks: firstly, an idealized scenario where 100% of the material is recycled as construction aggregate, and secondly, 100% of the material is disposed of. Under the standard calculation method, the GWP of sand-lime bricks in the case of full recycling is 128.51 [kg CO_2-eq.]. In contrast, in the case of total disposal, the total GWP is 140 [kg CO_2-eq.]. The modified method considers the potential future recycling rate of sand-lime bricks, with 52.64% expected to be recycled and the remaining 47.36% disposed of. Accordingly, the calculated GWP is 133.95 [kg CO_2-eq.], falling between the GWP values of the two scenarios simulated under the standard method. Further analysis shows that the GWP calculated by the modified method is 4% higher than that of the 100% downcycling simulation and 4% lower than that of the 100% disposal simulation. The carbon emission values derived from the modified method do not significantly differ from those obtained using the standard method. The application of the modified method for modifications the data of C3 and C4 exerts a relatively minor impact on the total GWP for those materials where the production stage constitutes a significant portion of the total GWP (see Figure 5-2).

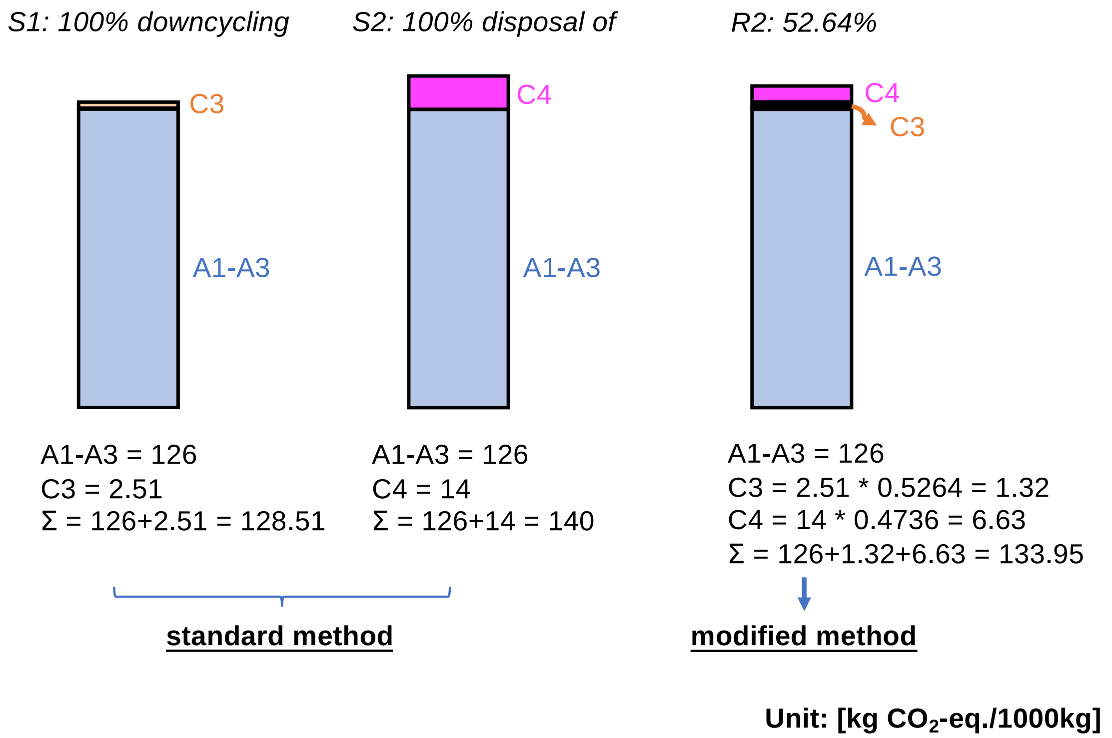


Figure 5-2: Comparison of carbon emissions for 1000 kg of sand-lime bricks estimated under the standard calculation method and the modified method

5.2.2. Limitation of the Correlation Analysis and Recommendations

Firstly, although varying degrees of negative correlation can be observed on the building level, building component level, and building material level, this negative correlation is not reflected in some cases. On the building level, the circularity potential of the massive wood construction variant is higher than that of the light wood construction variants. However, regarding GWP, the light wood construction variant outperforms the massive wood construction variant. In this case, GWP and UMI show a positive correlation, requiring analysis based on the calculation principles of GWP and UMI. The two building components with the most significant impact on the total GWP of the building are ceilings and roofs. The main difference between the massive wood construction variants and the light wood construction variants in these two building components is reflected in the load-bearing material. The massive wood construction uses the cross-laminated timber, while the light wood construction uses cross-laminated timber beams. Due to the much larger volume of wood used in the massive wood construction, its overall GWP value is higher than that of the light wood construction.

From the perspective of circularity potential analysis, the circularity performance of a building is derived by quantifying the total mass share of recycled materials used throughout the life cycle. In the case of the massive wood construction, the mass of the ceiling is much higher than in the light wood variant, and its proportion of recycled material is also higher, resulting in higher circularity potential. This positive correlation of GWP and UMI between the massive and light wood construction variants can also be observed in building components such as external walls, ceilings, and roofs. The choice between the massive wood and light wood construction variant in this study depends on the overall goals and priorities of the project. If reducing the carbon footprint is a priority, then the light wood construction variant with lower GWP values should be chosen. If promoting the recyclability of building materials and minimizing waste is the goal, then the massive wood construction variant with higher UMI values should be chosen. In addition, in terms of building insulation materials, there is no negative correlation between GWP and UMI in wood fiber insulation materials. Wood fiber exhibits higher GWP and circularity potential than other insulation materials. Its high circularity is based on wood fiber comprising 100% renewable raw materials. In the post-use stage, 70% of wood fiber enters closed-loop recycling, while the remaining 30% enters open-loop recycling.

In this study, the correlation between GWP and UMI was assessed by calculating the Spearman correlation coefficient and p-value. The p-value is used to test the null hypothesis, that is, there is no relationship between GWP and UMI. At all three levels, the calculated p-values exceeded the threshold of 0.05, meaning the null hypothesis cannot be rejected. This result indicates that all the negative correlations observed within the framework of this study are not statistically significant. A potential reason is the insufficient data on each level, leading to a lack of statistical power. Specifically, the analysis on the building level was based on four datasets; on the building component level, the external walls were analyzed with four datasets, ceilings and roofs with three each, while foundations, windows, and internal walls were only supported by two datasets each; at the building material level, insulation materials were analyzed with five datasets, load-bearing materials, and exterior wall includes with four each, and interior wall was only supported with two datasets. For a more robust study of the correlation between these two metrics, it is necessary in future studies to increase the number of datasets on each level to support the analysis.

6. Conclusion

In the context of carbon neutrality and the circular economy, the construction industry must take action to enhance its ecological benefits and sustainable development at the community and city scales. This paper systematically assesses the GWP, circularity potential, and their correlation for four building construction variants—sand-lime brick, brick, massive wood, and light wood—along with their six building components within the scope of the research project ECO+. The findings of the paper are crucial for researchers to understand the impact of choosing different building construction variants. Additionally, it provides deeper insights for designers into the sources of carbon emissions and circularity potential on the building materials, components, and building levels, facilitating the further development of the research project ECO+.

The study measured the embodied carbon emissions of the building materials during production, replacement, and EoL stages and assessed their circularity potential. The results of LCA indicate that the wood construction variants are superior to the brick construction variants. Given the limitations of the framework, future research should incorporate both embodied and operational carbon to fully simulate the carbon emissions throughout the lifecycle of brick and wood construction variants. For building materials that require replacement during the lifespan of the building, the carbon emissions generated during both their production phase and at the EoL stage are doubled. This duplication underscores the necessity for more research into extending the lifespan of such materials, which has a positive impact on reducing the overall embodied carbon emissions of buildings. The circularity potential analysis demonstrates that the wood construction variants have a higher circularity potential than the brick construction variants. The brick construction variants have negative environmental impacts, notably high embodied carbon, and low recyclability; therefore, they are not recommended within the context of this paper. The results of the correlation analysis revealed a certain negative correlation between GWP and UMI on the levels of building, building components, and building materials, indicating that variants with lower GWP often exhibit higher recyclability. In contrast, those with higher GWP typically show lower recyclability. The results of the correlation coefficient calculations also corroborate the same findings. The obtained Spearman correlation coefficients range from 0 to -1, indicating varying degrees of negative correlation between GWP and UMI. However, significance analysis shows that this negative correlation is not statistically significant. Future research could enhance statistical robustness by including additional construction variants such as concrete or hybrid structures. The two brick construction variants do not significantly differ in carbon emissions and circularity potential. Regarding wood construction variants, the light wood construction has an advantage in GWP over the massive wood, while the massive wood performs better in recycling potential. The final selection of which wood construction variant to use should be guided by the priorities of the research project ECO+ and consider other effective sustainability indicators when necessary. In terms of building materials, wood materials are recommended for use in load-bearing and wall cladding materials, mineral materials are recommended for use in insulation materials, and fossil materials are not recommended. Concrete and cement, characterized by their higher GWP and lower circularity potential, are extensively used in the foundations and ceilings, resulting in a significant environmental burden. Currently, the circularity potential of concrete and cement is primarily limited to downcycling in the post-use phase. Enhancing the utilization of secondary materials inputs in the pre-use phase is crucial for improving the recyclability of these materials. Simultaneously, given the advantages of wood in carbon neutrality and circularity potential, more research on wooden foundation practices is needed.

This paper employs a modified recycling modeling method for the LCA of buildings. However, this approach has certain limitations. Firstly, a discrepancy between calculated and actual carbon emissions of materials could lead to misguidance. Secondly, this method has minimal impact on the total GWP for certain materials.

Regarding the first point, there is a need to develop more comprehensive methods for recycling modeling. Integrating share of recycled material pre-use and recycling rates post-use of building materials into LCA analysis in the early design stages is undoubtedly complex. It requires a database to provide carbon emissions of materials undergoing recycling at different quality levels. The recyclability of materials is related to various factors, such as the connection methods between structural layers of building components, the value of materials, and the labor and cost of component dismantling. An acknowledged database providing existing and future potential share of recycled material inputs and recycling rates post-use for different materials is essential. Despite the early stage of the circular economy in the building industry, the increasing pressure of the construction sector on the global ecosystem underlines the urgency of incorporating material recyclability into building regulations. Therefore, it is necessary to develop tools that can more accurately include material recyclability in LCA analyses, aiding designers in better dealing with the trade-offs between GWP and circularity potential. Such tools also facilitate better communication between designers and stakeholders to achieve sustainability goals.

As for the second point, especially for materials whose major contribution to total GWP is from the production phase, significantly reducing their GWP requires addressing the carbon emissions generated during the production stage. This can be achieved by increasing the use of secondary materials or renewable resources in the pre-use phase. Further reduction in carbon emissions generated by the recycling process will make the benefits of recycling more significant.

In this paper, an in-depth assessment of the circularity potential of building materials was conducted through UMI. This assessment process highlights the necessity of establishing standardized procedures for circularity potential assessment within the construction industry, ensuring the scientific validity of design evaluations. Moreover, standardized assessments of circularity potential can motivate stakeholders, further promoting sustainable development and the practice of a CE in the construction industry. Finally, to fully realize the potential recycling of building materials, further research is necessary to enhance the current recycling rate of materials with the objective of achieving high-grade EoL scenarios. Choosing disassembly-friendly connection materials represents an effective approach. As engineers, we are responsible for integrating circular-oriented design principles in the early design phase, considering the flow of building materials throughout their entire lifecycle.

Literature

Adams, K., Osmani, M., Thorpe, A., Thornback, J. (2017). *Circular economy in construction: current awareness, challenges and enablers.* Proceedings of the Institution of Civil Engineers - Waste and Resource Management. 170. 1-11. 10.1680/jwarm.16.00011.

Al-Obaidy, M.; Courard, L.; Attia, S. (2022). *A Parametric Approach to Optimizing Building Construction Systems and Carbon Footprint: A Case Study Inspired by Circularity Principles*. Sustainability 2022, 14, 3370. https://doi.org/10.3390/su14063370

Allacker, K., Mathieux, F., Manfredi, S., Pelletier, N., De Camillis, C., Ardente, F., Pant, R. (2014). *Allocation solutions for secondary material production and end of life recovery: Proposals for product policy initiatives, Resources, Conservation and Recycling,* Volume 88, 2014, Pages 1-12, ISSN 0921-3449, https://doi.org/10.1016/j.resconrec.2014.03.016.

Anand, C.K., & Amor, B. (2017). *Recent developments, future challenges and new research directions in LCA of buildings: A critical review.* Renewable & Sustainable Energy Reviews, 67, 408-416.

Biccari, C.D., Abualdenien, J., Borrmann, A., Corallo, A. (2019). *A BIM-Based Framework to Visually Evaluate Circularity and Life Cycle Cost of buildings.* IOP Conference Series: Earth and Environmental Science. 290. 012043. 10.1088/1755-1315/290/1/012043.

Bilal, M., Khan, K.I.A., Thaheem, M.J., Nasir, A.R. (2020). *Current state and barriers to the circular economy in the building sector: Towards a mitigation framework*. Journal of Cleaner Production. 276. 123250. 10.1016/j.jclepro.2020.123250.

Biron, M. (2016). *15 - EcoDesign*, Editor(s): Michel Biron, Material Selection for Thermoplastic Parts, William Andrew Publishing, 2016, Pages 603-653, ISBN 9780702062841, https://doi.org/10.1016/B978-0-7020-6284-1.00015-5.

Brändström, J., Saidani, M. (2022). *Comparison between circularity metrics and LCA: A case study on circular economy strategies*, Journal of Cleaner Production, Volume 371, 2022, 133537, ISSN 0959-6526, https://doi.org/10.1016/j.jclepro.2022.133537.

Buyle, M., Braet, J., Audenaert, A. (2013). *Life cycle assessment in the construction sector: A review, Renewable and Sustainable Energy Reviews*, Volume 26, 2013, Pages 379-388, ISSN 1364-0321, https://doi.org/10.1016/j.rser.2013.05.001

Cabeza, L.F., Rincón, L., Vilariño, M.V., Perez, G., Castell, A. (2014). *Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: A review. Renewable and Sustainable Energy Reviews*. 29. 394-416. 10.1016/j.rser.2013.08.037.

Chen, Z., Feng, Q., Yue, R., Chen, Z., Moselhi, O., Soliman, A., Hammad, A., An, C. (2022). *Construction, renovation, and demolition waste in landfill: a review of waste characteristics, environmental impacts, and mitigation measures*. Environmental Science and Pollution Research. 29. 1-18. 10.1007/s11356-022-20479-5.

Diaz-Balteiro, L., Romero, C., & García de Jalón, S. (2022). *An analysis of the degree of circularity of the wood products industry in Europe.* Journal of Industrial Ecology, 26, 1350– 1363. https://doi-org.eaccess.tum.edu/10.1111/jiec.13257

Diemer, A., Dierickx, F. (2020). *Circular Economy, A new Paradigm For Europe?*. https://www.researchgate.net/publication/340793864_Circular_Economy_A_new_Paradigm_For_Europe

Dräger, P., Letmathe, P., Reinhart, L. et al. (2022). *Measuring circularity: evaluation of the circularity of construction products using the ÖKOBAUDAT database*. Environ Sci Eur 34, 13 (2022). https://doi.org/10.1186/s12302-022-00589-0

Eberhardt, L.C.M., Birgisdottir, H., & Birkved, M. (2019). *Potential of Circular Economy in Sustainable Buildings. IOP Conference Series: Materials Science and Engineering,* 471, Article 092051. https://doi.org/10.1088/1757-899X/471/9/092051

Ekins, P., Domenech, T., Drummond, P., Bleischwitz, R., Hughes, N. and Lotti, L. (2019). *"The Circular Economy: What, Why, How and Where",* Background paper for an OECD/EC Workshop on 5 July 2019 within the workshop series "Managing environmental and energy transitions for regions and cities", Paris

Ekvall, T., Björklund, A., Sandin, G., Jelse, K. (2020). *Modeling recycling in life cycle assessment.* https://www.researchgate.net/publication/344364006_Modeling_recycling_in_life_cycle_assessment/citations

Elia, V., Gnoni, M.G., Tornese, F. (2017). *Measuring circular economy strategies through index methods: A critical analysis*, Journal of Cleaner Production, Volume 142, Part 4, 2017, Pages 2741-2751, ISSN 0959-6526, https://doi.org/10.1016/j.jclepro.2016.10.196

Ellen MacArthur Foundation. (undated). *What is a circular economy?.* https://www.ellenmacarthurfoundation.org/topics/circular-economy-introduction/overview

Ellen MacArthur Foundation. (undated). *Reimagining our buildings and spaces for a circular economy*. https://www.ellenmacarthurfoundation.org/topics/built-environment/overview

Ellen MacArthur Foundation. (2013). *Towards the circular economy Vol. 1: an economic and business rationale for an accelerated transition*. https://www.ellenmacarthurfoundation.org/towards-the-circular-economy-vol-1-an-economic-and-business-rationale-for-an

Ellen MacArthur Foundation. (2014). *Towards the circular economy Vol. 3: accelerating the scale-up across global supply chains (2014).* https://www.ellenmacarthurfoundation.org/towards-the-circular-economy-vol-3-accelerating-the-scale-up-across-global

Ellen MacArthur Foundation. (2019). *The butterfly diagram: visualising the circular economy.* https://www.ellenmacarthurfoundation.org/circular-economy-diagram?gad_source=1&gclid=Cj0KCQiAyKurBhD5ARIsALamXaG-T5kB_2IO51kcQ7qxlWlVn8zqRCFNmsaPpKTn87nWrri_5DqzMP4aArqfEALw_wcB

European Commission. (2020). *Circular economy action plan: The EU's new circular action plan paves the way for a cleaner and more competitive Europe*. https://environment.ec.europa.eu/strategy/circular-economy-action-plan_en

European Commission, Directorate-General for Environment, (2017). *Resource efficient use of mixed wastes improving management of construction and demolition waste : final report*, Publications Office. https://data.europa.eu/doi/10.2779/99903

Evangelista, L. & Brito, J. (2007). *Environmental life cycle assessment of concrete made with fine recycled concrete aggregates*. 789-794. https://www.researchgate.net/publication/235939400_Environmental_life_cycle_assessment_of_concrete_made_with_fine_recycled_concrete_aggregates/citations

Geissdoerfer, M., Savaget, P., Bocken, N.M.P., Hultink, E.J. (2017). *The Circular Economy – A new sustainability paradigm?*, Journal of Cleaner Production, Volume 143, 2017, Pages 757-768, ISSN 0959-6526, https://doi.org/10.1016/j.jclepro.2016.12.048

Ghisellini, P., Cialani, C., Ulgiati, S. (2016). *A review on circular economy: the expected transition to a balanced interplay of environmental and economic systems,* Journal of Cleaner Production, Volume 114, 2016, Pages 11-32, ISSN 0959-6526, https://doi.org/10.1016/j.jclepro.2015.09.007

Gillott, C., Mihkelson, W., Lanau, M., Cheshire, D., & Tingley, D. D. (2023). *Developing Regenerate: A circular economy engagement tool for the assessment of new* *and existing buildings*. Journal of Industrial Ecology, 27, 423–435. https://doi.org/10.1111/jiec.13377

Global Cement and Concrete Association. (2023). *Cement and concrete around the world*. https://gccassociation.org/concretefuture/cement-concrete-around-the-world/

Gogtay, N.J., Thatte U.M. (2017). *Principles of Correlation Analysis. J Assoc Physicians India.* 2017 Mar;65(3):78-81. PMID: 28462548. https://www.kem.edu/wp-content/uploads/2012/06/9-Principles_of_correlation-1.pdf

Gong. X.Z., Zuoren, N., Wang, Z.H., Cui, S.P., Gao, F., Zuo, T.Y. (2012). *Life Cycle Energy Consumption and Carbon Dioxide Emission of Residential Building Designs in Beijing A Comparative Study*. Journal of Industrial Ecology. 16. 10.1111/j.1530-9290.2011.00415.x.

Haas, W., Krausmann, F., Wiedenhofer, D. and Heinz, M. (2015). *How Circular is the Global Economy?: An Assessment of Material Flows, Waste Production, and Recycling in the European Union and the World in 2005*. Journal of Industrial Ecology, 19: 765-777. https://doi.org/10.1111/jiec.12244

Hart, J., Adams, K., Giesekam, J., Tingley, D.D., Pomponi, F. (2019). *Barriers and drivers in a circular economy: the case of the built environment*, Procedia CIRP, Volume 80, 2019, Pages 619-624, ISSN 2212-8271, https://doi.org/10.1016/j.procir.2018.12.015

Haupt, M., Zschokke, M. (2017). *How can LCA support the circular economy?—63rd discussion forum on life cycle assessment*, Zurich, Switzerland, November 30, 2016. Int J Life Cycle Assess 22, 832–837 (2017). https://doi.org/10.1007/s11367-017-1267-1

Herrmann, I.T., Moltesen, A. (2015). *Does it matter which Life Cycle Assessment (LCA) tool you choose? – a comparative assessment of SimaPro and GaBi*, Journal of Cleaner Production, Volume 86, 2015, Pages 163-169, ISSN 0959-6526, https://doi.org/10.1016/j.jclepro.2014.08.004

Holappa L. (2020). *A General Vision for Reduction of Energy Consumption and CO2 Emissions from the Steel Industry*. Metals. 2020; 10(9):1117. https://doi.org/10.3390/met10091117

International Energy Agency. (2022f). *Tracking Buildings 2022. Paris: International Energy Agency*. https://www.iea.org/reports/tracking-buildings-2021.

Kanters J. (2020). Circular Building Design: *An Analysis of Barriers and Drivers for a Circular Building Sector.* Buildings. 2020; 10(4):77. https://doi.org/10.3390/buildings10040077

Kerr, J., Rayburg, S., Neave, M., Rodwell, J. (2022). *Comparative Analysis of the Global Warming Potential (GWP) of Structural Stone, Concrete and Steel Construction Materials*. Sustainability. 2022; 14(15):9019. https://doi.org/10.3390/su14159019

Khadim,N., Agliata, R., Marino, A., Thaheem, M.J., Mollo, L. (2022). *Critical review of nano and micro-level building circularity indicators and frameworks, Journal of Cleaner Production*, Volume 357, 2022, 131859, ISSN 0959-6526, https://doi.org/10.1016/j.jclepro.2022.131859

Kirchherr, J., Reike, D., Hekkert, M. (2017). *Conceptualizing the circular economy: An analysis of 114 definitions, Resources, Conservation and Recycling*, Volume 127, 2017, Pages 221-232, ISSN 0921-3449, https://doi.org/10.1016/j.resconrec.2017.09.005

Knoeri, C., Sanyé-Mengual, E., Althaus, H.J. (2013). *Comparative LCA of recycled and conventional concrete for structural applications.* Int J Life Cycle Assess 18, 909–918 (2013). https://doi-org.eaccess.tum.edu/10.1007/s11367-012-0544-2

Korhonen, J., Honkasalo, A., Seppälä, J. (2018). *Circular Economy: The Concept and its Limitations*, Ecological Economics, Volume 143, 2018, Pages 37-46, ISSN 0921-8009, https://doi.org/10.1016/j.ecolecon.2017.06.041

Lieder, M., Rashid, A. (2016). *Towards circular economy implementation: a comprehensive review in context of manufacturing industry*, Journal of Cleaner Production, Volume 115, 2016, Pages 36-51, ISSN 0959-6526, https://doi.org/10.1016/j.jclepro.2015.12.042.

Li, S.H., Xie, H. (2013). *Building professionals' attitudes towards the use of wood in building design and construction in Taiwan*. Eur. J. Wood Prod. 71, 497–505 (2013). https://doi.org/10.1007/s00107-013-0688-1

Lotteau, M., Loubet, P., Pousse, M., Dufrasnes, E., Sonnemann, G. (2015). *Critical review of life cycle assessment (LCA) for the built environment at the neighborhood scale, Building and Environment*, Volume 93, Part 2, 2015, Pages 165-178, ISSN 0360-1323, https://doi.org/10.1016/j.buildenv.2015.06.029.

Milaj, K., Sinha, A., Miller, T.H., Tokarczyk, J.A.. (2017). *Environmental utility of wood substitution in commercial buildings using life-cycle analysis*. Wood and Fiber Science. 49. 338-358.

Miller, S.A., Monteiro, P.J.M., Ostertag, C., Horvath, A. (2016). *Concrete mixture proportioning for desired strength and reduced global warming potential, Construction and Building Materials*, Volume 128, 2016, Pages 410-421, ISSN 0950-0618, https://doi.org/10.1016/j.conbuildmat.2016.10.081

Minunno, R., O'Grady, T., Morrison, G.M., Gruner R.L., Colling M. (2018). *Strategies for Applying the Circular Economy to Prefabricated Buildings*. Buildings. 2018; 8(9):125. https://doi.org/10.3390/buildings8090125

Munaro, M.R., Tavares, S.F., Bragança, L. (2020). *Towards circular and more sustainable buildings: A systematic literature review on the circular economy in the built environment*, Journal of Cleaner Production, Volume 260, 2020, 121134, ISSN 0959-6526, https://doi.org/10.1016/j.jclepro.2020.121134

Mondello, G., Salomone, R. (2020). *Chapter 10 - Assessing green processes through life cycle assessment and other LCA-related methods*, Editor(s): Angelo Basile, Gabriele Centi, Marcello De Falco, Gaetano Iaquaniello, Studies in Surface Science and Catalysis, Elsevier, Volume 179, 2020, Pages 159-185, ISSN 0167-2991, ISBN 9780444643377, https://doi.org/10.1016/B978-0-444-64337-7.00010-

Morseletto, P. (2020). *Targets for a circular economy, Resources, Conservation and Recycling*, Volume 153, 2020, 104553, ISSN 0921-3449, https://doi.org/10.1016/j.resconrec.2019.104553

Moynihan, M.C., Allwood, J.M. (2012). *The flow of steel into the construction sector, Resources,* Conservation and Recycling, Volume 68, 2012, Pages 88-95, ISSN 0921-3449, https://doi.org/10.1016/j.resconrec.2012.08.009.

Mo, Z., Gao, T., Qu, J., Cai, G., Cao, Z., Jiang, W. (2023). *An Empirical Study of Carbon Emission Calculation in the Production and Construction Phase of A Prefabricated Office Building from Zhejiang, China*. Buildings. 2023; 13(1):53. https://doi.org/10.3390/buildings13010053

Mrad, C.; Frölén Ribeiro, L. (2022). *A Review of Europe's Circular Economy in the Building Sector*. Sustainability 2022, 14, 14211. https://doi.org/10.3390/su142114211

Norouzi, M., Chàfer, M., Cabeza, L.C., Jiménez, L., Boer, D. (2021). *Circular economy in the building and construction sector: A scientific evolution analysis*, Journal of Building Engineering, Volume 44, 2021, 102704, ISSN 2352-7102, https://doi.org/10.1016/j.jobe.2021.102704

Núñez-Cacho, P., Górecki, J., Molina-Moreno, V., Antonio, F., Corpas-Iglesias, F.A., Corpas, F.A. (2018). *New Measures of Circular Economy Thinking In Construction Companies*. Journal of EU Research in Business. 2018. 10.5171/2018.909360.

Organization for Economic Co-operation and Development. (2019). *Global Material Resources Outlook to 2060: Economic Drivers and Environmental Consequences*. OECD Publishing, Paris. https://doi.org/10.1787/9789264307452-en

Parchomenko, A., Nelen, D., Gillabel, J., Rechberger, H. (2019). *Measuring the circular economy - A Multiple Correspondence Analysis of 63 metrics*. Journal of Cleaner Production, Volume 210, 2019, Pages 200-216, ISSN 0959-6526, https://doi.org/10.1016/j.jclepro.2018.10.357

Pascale, A.D., Arbolino, R., Szopik-Depczyńska, K., Limosani, M., Ioppolo, G. (2021). *A systematic review for measuring circular economy: The 61 indicators*, Journal of Cleaner Production, Volume 281, 2021, 124942, ISSN 0959-6526, https://doi.org/10.1016/j.jclepro.2020.124942

Peña, C., Civit, B., Gallego-Schmid, A. et al. (2021). *Using life cycle assessment to achieve a circular economy*. Int J Life Cycle Assess 26, 215–220 (2021). https://doi.org/10.1007/s11367-020-01856-z

Poolsawad, N, Chom-in, T, Samneangngam, J, et al. (2023). *Material circularity indicator for accelerating low-carbon circular economy in Thailand's building and construction sector.* Environ Prog Sustainable Energy. 2023; 42(4):e14105. doi:10.1002/ep.14105

Potting, J., Hekkert, M.P., Worrell, E., Hanemaaijer, A. (2017). *Circular Economy: Measuring innovation in the product chain*. https://www.researchgate.net/publication/319314335_Circular_Economy_Measuring_innovation_in_the_product_chain

Rigamonti, L., Mancini, E. (2021). *Life cycle assessment and circularity indicators*. Int J Life Cycle Assess 26, 1937–1942 (2021). https://doi.org/10.1007/s11367-021-01966-2

Rosen, A. (2021). *Urban Mining Index: Entwicklung einer Systematik zur quantitativen Bewertung der Kreislaufkonsistenz von Baukonstruktionen in der Neubauplanung*. Fraunhofer IRB Verlag. ISBN 9783738806069.

Sánchez-Garrido, A.J., Navarro, I.J., Yepes, V. (2022). *Multi-criteria decision-making applied to the sustainability of building structures based on Modern Methods of Construction*, Journal of Cleaner Production, Volume 330, 2022, 129724, ISSN 0959-6526, https://doi.org/10.1016/j.jclepro.2021.129724

Smol, M., Kulczycka, J., Avdiushchenko, A. (2017). *Circular economy indicators in relation to eco-innovation in European regions.* Clean Techn Environ Policy 19, 669–678 (2017). https://doi.org/10.1007/s10098-016-1323-8

SYSTEMIQ and Ellen MacArthur Foundation. (2017). *Achieving 'growth within' (2017)*. https://www.ellenmacarthurfoundation.org/achieving-growth-within

Tavares, V., Soares, N., Raposo, N., Marques, P., Freire, F. (2021). *Prefabricated versus conventional construction: Comparing life-cycle impacts of alternative* *structural materials*, Journal of Building Engineering, Volume 41, 2021, 102705, ISSN 2352-7102, https://doi.org/10.1016/j.jobe.2021.102705

United Nations Environment Programme. (2022). *2022 Global Status Report for Buildings and Construction*. https://www.unep.org/resources/publication/2022-global-status-report-buildings-and-construction

Zhang, C., Hu, M., Maio, F.D., Sprecher, B., Yang, X., Tukker, A. (2022). *An overview of the waste hierarchy framework for analyzing the circularity in construction and demolition waste management in Europe*. Science of The Total Environment, Volume 803, 2022, 149892, ISSN 0048-9697, https://doi.org/10.1016/j.scitotenv.2021.149892

Zhu Q. (2011). *Profiles: CO2 abatement in the cement industry*, IEA Clean Coal Centre: London, UK, 2011. https://usea.org/sites/default/files/062011_CO2%20abatement%20in%20the%20cement_ccc184.pdf

List of Figures

List of Tables

Appendix A: Architectural Draft Concept Variant 7

Appendix B: Material-Recycling-Content

	Recyclingmaterial	**Downcyclingmaterial**	**Neumaterial**	**nachwachsendes Neumaterial - nachhaltiger Anbau**	**nachwachsendes Neumaterial**	**Seite**
biotische Materialien	***19%***	***0%***	***5%***	***8%***	***68%***	***100%***
KVH	0%	0%	0%	0%	100%	71
BSH	0%	0%	5%	0%	95%	
Massivholzbretter, Thermoholz, Holzwerkstoffplatte	0%	0%	3%	97.5%	0%	78
Schindeln, Reet	0%	0%	0%	0%	100%	
Massivholz-, OSB-Platte, Spanplatte, Holzfaserplatte	3%	0%	6%	44%	47%	82
Massivholzdielen, Parkett	0%	0%	0%	0%	100%	85
Linoleum	5%	0%	18%	0%	78%	
Holzfaser-, Holzspandämmung	0%	0%	0%	0%	100%	91
Korkdämmplatte	0%	0%	0%	0%	100%	
Korkdämmgranulat	100%	0%	0%	0%	0%	
Zelluloseflocken	90%	0%	10%	0%	0%	
Hanffaser-, Jutefassermatte	43%	0%	3%	0%	55%	
Kokusfaserdämmung	0%	0%	5%	0%	95%	
Schilfrohrdämmmatte	0%	0%	2%	0%	98%	
Seegras-, Schafschurwolle	0%	0%	0%	0%	100%	
Pappe	100%	0%	0%	0%	0%	94
Papier	0%	0%	0%	0%	100%	
pflanzliche Dichtung	0%	0%	40%	0%	60%	
	Recyclingmaterial	**Downcyclingmaterial**	**Neumaterial**	**nachwachsendes Neumaterial - nachhaltiger Anbau**	**nachwachsendes Neumaterial**	**Seite**
metallische Materialien	***45%***	***0%***	***59%***	***0%***	***0%***	***103%***
Stahl (Walzprofil, Blech, Baustahl)	33%	0%	67%	0%	0%	71, 78
Aluminiumblech (lackiert)	50%	0%	50%	0%	0%	78
Zinkblech	30%	0%	70%	0%	0%	
Kupferblech	55%	0%	65%	0%	0%	
Recyclingkupferbleche	100%	0%	0%	0%	0%	
Aluminium Dampfsperre	0%	0%	100%	0%	0%	94
	Recyclingmaterial	**Downcyclingmaterial**	**Neumaterial**	**nachwachsendes Neumaterial - nachhaltiger Anbau**	**nachwachsendes Neumaterial**	**Seite**
fossile Materialien	***9%***	***0%***	***92%***	***0%***	***0%***	***100%***
PC-Platten	0%	0%	100%	0%	0%	78
Gussasphaltestrich	0%	0%	100%	0%	0%	85
Nylon-Teppichfliese	63%	0%	37%	0%	0%	
Polysyrol Hartschaum (EPS)	0%	0%	100%	0%	0%	91
Unterspannbahn (PE-HD)	0%	0%	100%	0%	0%	94
Dampfbremse (PE-LD)	0%	0%	100%	0%	0%	
Bitumenabdichtungsbahn	0%	0%	100%	0%	0%	
Abdichtungsbahn (EPDM)	5%	0%	95%	0%	0%	
	Recyclingmaterial	**Downcyclingmaterial**	**Neumaterial**	**nachwachsendes Neumaterial - nachhaltiger Anbau**	**nachwachsendes Neumaterial**	**Seite**
mineralische Materialien	***29%***	***0%***	***71%***	***0%***	***0%***	***100%***
Mauerstein (Kalksand, Porenbeton)	0%	0%	100%	0%	0%	71
Beton	40%	0%	60%	0%	0%	
Naturstein	0%	0%	100%	0%	0%	78
Faserzement- & Glasfaserbetonplatte	0%	0%	100%	0%	0%	
Klinker	0%	0%	100%	0%	0%	
Glas, Glaskeramik	70%	0%	30%	0%	0%	
Gipskartonplatte	2%	0%	98%	0%	3%	82
Lehmbauplatte	0%	0%	97%	2%	0%	
Estrichziegel	33%	0%	67%	0%	0%	85
Blähton	0%	0%	100%	0%	0%	91
Schaumglasdämmplatte	68%	0%	32%	0%	0%	
Schaumglasschotter	99%	0%	1%	0%	0%	
Glaswolle	80%	0%	20%	0%	0%	
Floatglas	10%	0%	90%	0%	0%	97

Appendix C: Material-Loop-Potential

	Recyclingmaterial	Downcyclingmaterial	Neumaterial	nachwachsendes Neumaterial - nachhaltiger Anbau	nachwachsendes Neumaterial	Seite
biotische Materialien	***27%***	***0%***	***8%***	***59%***	***6%***	***100%***
KVH	0%	0%	0%	100%	0%	71
BSH	0%	0%	0%	95%	5%	
Massivholzbretter, Thermoholz, Holzwerkstoffplatte	0%	0%	3%	97.5%	0%	78
Schindeln, Reet	0%	0%	0%	0%	100%	
Massivholz-, OSB-Platte, Spanplatte, Holzfaserplatte	53%	0%	6%	41%	0%	82
Massivholzdielen, Parkett	0%	0%	0%	100%	0%	85
Linoleum	5%	0%	18%	78%	0%	
Holzfaser-, Holzspandämmung	0%	0%	0%	100%	0%	91
Korkdämmplatte	0%	0%	0%	100%	0%	
Korkdämmgranulat	100%	0%	0%	0%	0%	
Zelluloseflocken	90%	0%	10%	0%	0%	
Hanffaser-, Jutefassermatte	45%	0%	3%	52%	0%	
Kokusfaserdämmung	0%	0%	5%	95%	0%	
Schilfrohrdämmmatte	2%	0%	98%	0%	0%	
Seegras-, Schafschurwolle	0%	0%	0%	100%	0%	
Pappe	100%	0%	0%	0%	0%	94
Papier	0%	0%	0%	100%	0%	
pflanzliche Dichtung	98%	0%	2%	0%	0%	
	Recyclingmaterial	**Downcyclingmaterial**	**Neumaterial**	**nachwachsendes Neumaterial - nachhaltiger Anbau**	**nachwachsendes Neumaterial**	**Seite**
metallische Materialien	***100%***	***0%***	***0%***	***0%***	***0%***	***100%***
Stahl (Walzprofil, Blech, Baustahl)	100%	0%	0%	0%	0%	71, 78
Aluminiumblech (lackiert)	98%	0%	2%	0%	0%	78
Zinkblech	100%	0%	0%	0%	0%	
Kupferblech	100%	0%	0%	0%	0%	
Recyclingkupferbleche	100%	0%	0%	0%	0%	
Aluminium Dampfsperre	100%	0%	0%	0%	0%	94
	Recyclingmaterial	**Downcyclingmaterial**	**Neumaterial**	**nachwachsendes Neumaterial - nachhaltiger Anbau**	**nachwachsendes Neumaterial**	**Seite**
fossile Materialien	***41%***	***13%***	***47%***	***0%***	***0%***	***100%***
PC-Platten	30%	0%	70%	0%	0%	78
Gussasphaltestrich	99%	0%	1%	0%	0%	85
Nylon-Teppichfliese	90%	0%	10%	0%	0%	
Polysyrol Hartschaum (EPS)	30%	0%	70%	0%	0%	91
Unterspannbahn (PE-HD)	0%	0%	100%	0%	0%	94
Dampfbremse (PE-LD)	0%	100%	0%	0%	0%	
Bitumenabdichtungsbahn	30%	0%	70%	0%	0%	
Abdichtungsbahn (EPDM)	45%	0%	55%	0%	0%	
	Recyclingmaterial	**Downcyclingmaterial**	**Neumaterial**	**nachwachsendes Neumaterial - nachhaltiger Anbau**	**nachwachsendes Neumaterial**	**Seite**
mineralische Materialien	***52%***	***0%***	***46%***	***0%***	***0%***	***98%***
Mauerstein (Kalksand, Porenbeton)	26%	0%	74%	0%	0%	71
Beton	40%	0%	60%	0%	0%	
Naturstein	0%	0%	100%	0%	0%	78
Faserzement- & Glasfaserbetonplatte	0%	0%	100%	0%	0%	
Klinker	20%	0%	80%	0%	0%	
Glas, Glaskeramik	100%	0%	0%	0%	0%	
Gipskartonplatte	99%	0%	1%	0%	0%	82
Lehmbauplatte	100%	0%	0%	0%	0%	
Estrichziegel	40%	0%	60%	0%	0%	85
Blähton	0%	0%	100%	0%	0%	91
Schaumglasdämmplatte	68%	0%	0%	0%	0%	
Schaumglasschotter	99%	0%	1%	0%	0%	
Glaswolle	80%	0%	20%	0%	0%	
Floatglas	50%	0%	50%	0%	0%	97

Appendix D: Circularity Potential Analysis Results: Legend Explanation

Pre-use

- recycling
- renewable primary resources, certified
- renewable primary resources
- quality levels that do not belong to CLP and LP

Post-use

- recyclable
- downcyclable, certified renewable
- energetically usable, certified renewable
- downcyclable
- energetically usable, renewable
- quality levels that do not belong to CLP and LP

Appendix E: Calculation Results of Spearman Correlation Coefficients

The computation of correlation coefficients in Microsoft Excel is conducted by the incorporation of the Real Statistics Resource Pack, an enhancement tool. For further information, please refer to the official website: https://real-statistics.com/

Building level:

Correlation Coefficients	
Pearson	-0,876237098
Spearman	**-0,8**
Kendall	-0,666666667
Spearman's coefficient (test)	
Alpha	0,05
Tails	2
rho	**-0,8**
t-stat	-1,885618083
p-value	**0,2**

Building component level:

Foundation:	
Correlation Coefficients	
Pearson	-0,999999999
Spearman	**-0,942809042**
Kendall	-0,894427191
Spearman's coefficient (test)	
Alpha	0,05
Tails	2
rho	**-0,942809042**
t-stat	-4
p-value	**0,057190958**

External wall:	
Correlation Coefficients	
Pearson	-0,926376551
Spearman	**-0,6**
Kendall	-0,333333333
Spearman's coefficient (test)	
Alpha	0,05
Tails	2
rho	**-0,6**
t-stat	-1,060660172
p-value	**0,4**

Window:	
Correlation Coefficients	
Pearson	-1
Spearman	**-1**
Kendall	-1
Spearman's coefficient (test)	
Alpha	0,05
Tails	2
rho	**-1**
t-stat	-inf
p-value	**0**

Internal wall:	
Correlation Coefficients	
Pearson	-0,999999807
Spearman	**-0,942809042**
Kendall	-0,894427191
Spearman's coefficient (test)	
Alpha	0,05
Tails	2
rho	**-0,942809042**
t-stat	-4
p-value	**0,057190958**

Ceiling:	
Correlation Coefficients	
Pearson	-0,725125985
Spearman	**-0,777777778**
Kendall	-0,6
Spearman's coefficient (test)	
Alpha	0,05
Tails	2
rho	**-0,777777778**
t-stat	-1,75
p-value	**0,222222222**

Roof:	
Correlation Coefficients	
Pearson	-0,952348409
Spearman	**-0,777777778**
Kendall	-0,6
Spearman's coefficient (test)	
Alpha	0,05
Tails	2
rho	**-0,777777778**
t-stat	-1,75
p-value	**0,222222222**

Building material level:

Load-bearing:	
Correlation Coefficients	
Pearson	-0,880311278
Spearman	**-0,8**
Kendall	-0,666666667
Spearman's coefficient (test)	
Alpha	0,05
Tails	2
rho	**-0,8**
t-stat	-1,885618083
p-value	**0,2**

Insulation:	
Correlation Coefficients	
Pearson	-0,602271054
Spearman	**-0,307793506**
Kendall	-0,316227766
Spearman's coefficient (test)	
Alpha	0,05
Tails	2
rho	**-0,307793506**
t-stat	-0,560315526
p-value	**0,614384003**

Wall cladding, interior:	
Correlation Coefficients	
Pearson	-0,680783001
Spearman	**-0,4**
Kendall	-0,333333333
Spearman's coefficient (test)	
Alpha	0,05
Tails	2
rho	**-0,4**
t-stat	-0,6172134
p-value	**0,6**