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ERASMUS MUNDUS JOINT MASTER DEGREE

MASTER DEGREE IN SUSTAINABLE DESIGN, CONSTRUCTION AND MANAGEMENT OF THE BUILT ENVIRONMENT

MBUILD

ASSESSING THE RELIABILITY OF EARLY-STAGE BIM-BASED LIFE CYCLE ASSESSMENT ACROSS LEVELS OF DEVELOPMENT

NAHOM KIFLEMARIAM ABRAHAM

Supervision: Prof. Dr.-Ing. Walter Sharmak (THM)

Giessen, 2026

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Dedicated to my father, Kiflemariam, my mother, Tzigereda, and my three sisters, Sara, Ruth, and Sofia, whose support has accompanied me throughout my journey. I am deeply grateful for their presence in my life.

"In the end, we will conserve only what we love; we will love only what we understand, and we will understand only what we are taught."

Baba Dioum

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¡Muchas gracias!

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Muito obrigada!

ABSTRACT

Building Information Modelling (BIM)-based Life Cycle Assessment (LCA) has become an important tool for evaluating the embodied carbon of buildings. Yet, the reliability of such assessments is strongly influenced by the maturity of the underlying BIM model, expressed through its Level of Development (LOD). While early-stage LCA offers the greatest potential to influence design decisions, the data available at low LOD stages is often incomplete, raising questions about the validity of results obtained before a design is fully developed. This thesis addresses this tension by systematically comparing the embodied carbon results of the same case study building modelled at LOD 100, LOD 200, and LOD 300 to quantify the deviation introduced by model maturity and identify which building elements are most responsible for this deviation.

The study was developed around a prototype single-family residential building, modelled in Autodesk Revit 2025 and assessed using the One Click LCA platform, with the Ökobaudat database applied as the source of Environmental Product Declaration (EPD) data compliant with EN 15804 A2. The research strategy proceeded through three main phases. First, three parallel BIM models were developed, corresponding to LOD 100, 200, and 300, following the BIMForum LOD Specification, with consistent structural material assumptions applied wherever possible to preserve internal comparability across stages. Second, quantities were mapped to EPD-backed material data through automatic and manual mapping procedures, including corrections for discrete framing members such as metal studs and timber rafters. Third, the resulting Global Warming Potential (GWP) values, focused on the A1–A3 production stage, were compared across LOD stages at both the total building level and the individual building-element level, using percentage deviation from the LOD 300 model as the reference point, because it represented the most developed and internally detailed stage assessed in this study.

The analysis achieved four principal objectives. It quantified the overall deviation in embodied carbon between early and detailed BIM models, with the LOD 300 reference building normalising to approximately 246.5 kg CO2e/m² for GWP Fossil and 239.7 kg CO2e/m² for GWP Total, and identified two recurring mechanisms behind this deviation: geometric refinement, where discrete structural members were treated as continuous solid layers at lower LOD, and material scope expansion, where components such as window frames were introduced only at LOD 300. It identified External Walls as the largest contributor to embodied carbon (36.5%), while Stairs was the category with the smallest contribution (1.1%) despite showing the largest relative deviation, demonstrating that negligibility must be defined by absolute contribution, not deviation magnitude. Finally, findings were benchmarked against DGNB reference values and existing BIM-LCA literature, confirming that early-stage results cannot be treated as precise.

The thesis concludes that model maturity exerts a decisive but mechanism-specific influence on the reliability of BIM-based embodied carbon assessments, offering practical guidance on which building components and modelling decisions warrant closer scrutiny at early design stages.

Keywords: Building Information Modelling (BIM), Life Cycle Assessment (LCA), Level of Development (LOD), Global Warming Potential (GWP), Early-Stage Design Reliability

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SYMBOLS, ACRONYMS AND ABBREVIATIONS

A – element/wall area [m^2]

Awall – wall area [m^2]

Δ% – percentage deviation from LOD 300 reference value [%]

H – wall/element height [m]

L1, L2 – building length dimensions [m]

m – mass [kg]

mstuds – total stud mass [kg]

n – number of discrete structural members [–]

nstuds – number of studs [–]

ρ – material density [kg/m3]

s – centre-to-centre spacing of studs/rafters [mm]

t – layer thickness [mm]

V – volume [m3]

°C – degrees Celsius

A1–A3 – Product Stage

A4–A5 – Construction Process Stage

ADPE – Abiotic Depletion Potential (elements)

ADPF – Abiotic Depletion Potential (fossil resources)

AEC – Architecture, Engineering and Construction

AIA – American Institute of Architects

AP – Acidification Potential

ARGE – Arbeitsgemeinschaft für zeitgemäßes Bauen e.V.

B1–B7 – Use Stage

BIM – Building Information Modelling

BMDV – Bundesministerium für Digitales und Verkehr

BMVg – Bundesministerium der Verteidigung

BMWSB – Bundesministerium für Wohnen, Stadtentwicklung und Bauwesen

BNB – Bewertungssystem Nachhaltiges Bauen

BRE – Building Research Establishment

C1–C4 – End-of-Life Stage

CDE – Common Data Environment

CEN – European Committee for Standardisation

CH4 – Methane

CO2 – Carbon Dioxide

CO2-eq – Carbon Dioxide Equivalent

COP21 – 21st Conference of the Parties

DGNB – Deutsche Gesellschaft für Nachhaltiges Bauen

DIN – Deutsches Institut für Normung

EIR – Employer's Information Requirements

EN – European Norm

EP – Eutrophication Potential

EPBD – Energy Performance of Buildings Directive

EPD – Environmental Product Declaration

GAW – Global Atmosphere Watch

GBCT – Global Buildings Climate Tracker

GEG – Gebäudeenergiegesetz

GFA – Gross Floor Area

GHG – Greenhouse Gas

GIA – Gross Internal Area

GWP – Global Warming Potential

IBU – Institut Bauen und Umwelt

IFC – Industry Foundation Classes

IPCC – Intergovernmental Panel on Climate Change

ISO – International Organization for Standardization

LCA – Life Cycle Assessment

LCI – Life Cycle Inventory

LCIA – Life Cycle Impact Assessment

LOD – Level of Development

LoD – Level of Detail

LOG – Level of Geometry

LOI – Level of Information

LOIN – Level of Information Need

N2O – Nitrous Oxide

NDC – Nationally Determined Contribution

NSA – Net Surface Area

ODP – Ozone Depletion Potential

PCR – Product Category Rules

PEF – Product Environmental Footprint

POCP – Photochemical Ozone Creation Potential

QNG – Qualitätssiegel Nachhaltiges Gebäude

UNFCCC – United Nations Framework Convention on Climate Change

WDP – Water Depletion Potential

WMO – World Meteorological Organization

EFH – Einfamilienhaus

GWB – Gypsum Wallboard

kg – kilogram

m – metre

m^2 – square metre

m^3 – cubic metre

mm – millimetre

No. – Number

1
INTRODUCTION

1.1. BACKGROUND AND CONTEXT

Greenhouse gases (GHGs) are essential for warming our planet; without them, Earth would not support life as we know it. One of the most significant GHGs in the atmosphere is carbon dioxide (CO_2), which is released through both human activities such as the burning of fossil fuels, including coal, oil, and natural gas and natural events such as wildfires and volcanic eruptions. In recent decades, satellite and ground-based measurements have recorded a sharp increase in atmospheric CO_2 concentrations. According to NASA, current CO_2 levels are approximately 50% higher than they were in the pre-industrial era of the 18th century. [1]. This rise is directly linked to the accelerated burning of fossil fuels since the onset of industrialisation, driven by growing demands for electricity, transportation, and large-scale deforestation. Remarkably, approximately 45% of all cumulative CO_2 emissions in human history have been produced since the year 2000 [2]. Accounting for all greenhouse gases, average annual global net anthropogenic GHG emissions reached their highest decadal level on record during 2010–2019, averaging 56 $GtCO_2$-equivalent per year. [3].

This sustained rise in GHG emissions has caused measurable warming of the planet. The IPCC has observed that each of the last four decades has been successively warmer than any decade preceding it since 1850 [4]. Extreme heat events have become more frequent and intense globally, with numerous countries recording their highest-ever temperatures in recent years [5]. The IPCC unequivocally states that "human influence has warmed the atmosphere, ocean and land", estimating that human activities have caused approximately 1.07°C of increase in global mean surface temperature above pre-industrial levels [4].

In response to this alarming scientific evidence, world leaders convened in Paris in 2015 at the UN Climate Change Conference (COP21) and adopted the Paris Agreement, a legally binding international treaty to combat climate change, currently ratified by 194 Parties. The primary goal of the Agreement is to limit the increase in global average temperature to well below 2°C above pre-industrial levels, while pursuing efforts to limit it to 1.5°C. Under this framework, each country is required to submit a Nationally Determined Contribution (NDC), a national climate action plan detailing how it will reduce emissions, which must be updated every five years with increasing ambition. NDCs cover both mitigation measures to reduce GHG emissions and adaptation measures to manage unavoidable climate impacts [6]. However, despite this progress, global emissions continue to rise. The NDCs submitted by 2021 projected that GHG emissions in 2030 would still result in warming that significantly exceeds 1.5°C, making it increasingly difficult to limit warming to below 2°C [4].

At the regional level, the European Union has responded to this challenge by implementing some of the world's most ambitious climate legislation, setting a legally binding path toward becoming the first continent to reach climate neutrality by 2050. The European Green Deal, launched in 2019, aims to

reduce GHG emissions by at least 55% by 2030 compared to 1990 levels, with a further proposed target of 90% reduction by 2040 [7].In November 2025, the EU also submitted its revised Nationally Determined Contribution (NDC) to the UNFCCC, reinforcing these commitments at the international level [8].

The building sector is one of the largest contributors to global GHG emissions, accounting for approximately 39% of global energy-related carbon emissions [9]. According to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), the building sector was responsible for 21% of global GHG emissions, amounting to 12 $GtCO_2$-eq in 2019 [10]. Operational energy-related CO_2 emissions, the energy consumed while buildings are in use, increased by approximately 1% from 2021 to 2022, and according to the Global Buildings Climate Tracker, the Architecture, Engineering and Construction (AEC) sector is not on track to achieve decarbonisation by 2050 [11]. Moreover, with the global population estimated to reach 10 billion by 2050, the global building stock is expected to double in floor area, making sustainable construction decisions today critically consequential for long-term climate outcomes [12].

Embodied carbon in buildings refers to the greenhouse gas emissions produced during the extraction, manufacturing, and transport of building materials, as well as on-site construction and end-of-life demolition or re-use. Currently, 11% of global energy-related carbon emissions originate from building materials and construction, with embodied carbon accounting for approximately 25% of total building sector emissions, while operational energy accounts for the remaining 75%. However, this balance is changing as the focus on renewable energy and improved insulation reduces operational emissions; embodied carbon is projected to reach a near-equal share by 2050 [13]. According to Architecture 2030, just three materials concrete, steel, and aluminium are responsible for approximately 23% of total global emissions, making reducing embodied carbon an urgent necessity [14]. This shift is now reflected in policy through the revised Energy Performance of Buildings Directive (EPBD, Directive 2024/1275/EU); the EU is pushing building decarbonisation beyond operational energy efficiency, mandating whole life-cycle carbon assessments for all new buildings from 2030 (European Parliament & Council, 2024). Historically focused on operational energy alone, this regulatory shift clearly signals the growing importance of embodied carbon in achieving climate neutrality [15].

Life Cycle Assessment (LCA) is a standardised methodology used to quantify the environmental impacts of a product or system throughout its entire life cycle from raw material extraction to end-of-life demolition, governed by ISO 14040:2006 (principles and framework) and ISO 14044:2006 (requirements and guidelines) [16]. For buildings specifically, EN 15978 defines the calculation method to assess environmental performance by dividing the life cycle into distinct stages: material production and transport (Modules A1–A5), use phase (Modules B1–B7), end of life (Modules C1–C4), and beyond the system boundary (Module D) [17]. LCA relies on Environmental Product Declarations (EPDs), standardised documents that quantify the environmental impact of construction materials, governed by EN 15804 [18]. In the German context, LCA is embedded in national sustainability certification systems, including the Bewertungssystem Nachhaltiges Bauen (BNB) for federal buildings and the DGNB, which was the first certification system worldwide to incorporate full life cycle environmental assessment [19]. While LCA provides the assessment framework for quantifying embodied carbon, it requires accurate quantity and material data from the building model, a need that Building Information Modelling (BIM) is increasingly fulfilling.

Building Information Modelling (BIM) is a digital methodology that integrates geometric and semantic data, enabling stakeholders to collaborate on designing, constructing, and managing building projects [20]. In Germany, BIM became mandatory for all federally funded infrastructure and building projects from January 2021, marking a significant step toward the digitalisation of the construction sector [21]. BIM models contain geometric and material information that facilitates automated quantity takeoffs for LCA, reducing the time and effort required for manual data extraction. Several BIM-LCA integration approaches have been developed to enable faster, more consistent, and reliable environmental

assessments within the design workflow [22]. However, as BIM models progress through Levels of Development (LOD) from early schematic massing (LOD 100) through developed design (LOD 200) to detailed construction documentation (LOD 300), the completeness of material and geometric information increases significantly. LCA is most impactful at early design stages (LOD 100–200), when major material and structural decisions can still be influenced, but BIM models at these stages are the least complete, raising a fundamental question about the reliability of LCA results at different LODs [23]. Existing research confirms that LOD significantly influences LCA outputs, yet standardised guidance on which LOD produces sufficiently reliable LCA results for residential buildings remains limited, motivating the present study [24].

1.2. RESEARCH MOTIVATION

As BIM becomes increasingly important in the German context and globally and mandatory on certain public projects, its value as a digital platform spanning the entire construction process is widely recognised. Simultaneously, LCA is becoming a regulatory requirement in German practice through certification systems such as BNB and DGNB, meaning that practitioners are now expected to conduct environmental assessments as part of standard project delivery. Furthermore, the revised Energy Performance of Buildings Directive requires all EU member states to calculate the life-cycle Global Warming Potential, an indicator quantifying the climate impact of a building across both operational and embodied emissions for all new buildings from 2030[25], [26], [27]. In practice, however, LCA is often conducted late in the design process, when the BIM model has already reached LOD 300 and detailed material data becomes available. Yet it is the early design decisions concerning structural systems, material choices, and building geometry that have the greatest influence on embodied carbon, and these decisions are frequently made without any quantitative environmental assessment [9]. To date, no evidence-based guidance exists for German practitioners on at which stage of the BIM workflow LCA can be performed reliably.

While BIM-LCA integration has been extensively studied, most research focuses on LOD 300 or higher, where detailed material information is available. Very few studies explicitly examine the reliability of LCA results at LOD 100 and LOD 200 and how these compare with assessments performed on fully detailed models. As highlighted in the literature, early-stage BIM models are characterised by incomplete and uncertain data, which raises fundamental questions about the credibility of environmental results at these stages [28], [29].

As a Master's student in Sustainable Design, Construction, and Management of the Built Environment, I see the intersection of BIM and LCA as a central and timely research area that directly addresses how to make the construction process more environmentally responsible. With rapid advances in digitalisation and the growing availability of BIM tools and LCA software, the AEC sector has significant potential to improve its environmental performance through data-driven design decisions. This dissertation focuses on early design decision-making in the context of a German residential building, to provide practitioners with more reliable guidance for conducting LCA at different stages of BIM development, ultimately supporting more sustainable outcomes in construction projects.

1.3. PROBLEM STATEMENT

From conducting a relevant literature review, most case studies on BIM-based LCA do not clearly specify the Level of Development (LOD) of the model used. Furthermore, it is unrealistic to assign the same LOD to every building element, as each element progresses at a different rate during the design phase, resulting in a lack of consistency in the LOD–LCA relationship [28].

Practitioners agree that design choices made at the early stages of a project greatly affect LCA results, and as the model develops, it becomes increasingly difficult to make changes. Informed decision-making in the early design process is therefore important. However, since information about materials and quantities in the early design stage is limited, the resulting embodied GWP values may be misleading. Contrasting results have been found across previous studies, largely because they are not standardised; they differ in model maturity, building typology, modelling assumptions, and the environmental databases used [28], [29].

Despite the progress achieved, a more standardised relationship between model maturity and the way LCA is applied remains necessary. Furthermore, a better understanding of how quantities and environmental results change between design stages is needed, so that estimation rules and adjustment methods can be developed for use in early-stage models.

1.4. AIM OF THE STUDY

The main aim of this study is to understand, evaluate, and compare the embodied carbon generated by a building through Life Cycle Assessment (LCA) conducted at three Levels of Development, LOD 100, LOD 200, and LOD 300. This will be achieved by modelling a typical German residential building in Revit at each of the three LODs and quantifying how embodied Global Warming Potential (GWP) changes from one level to another, using One Click LCA with the German Ökobaudat database. The results will then be compared with findings from previous studies in the literature. This research aims to benefit German practitioners and researchers requiring evidence-based guidance on when BIM-based LCA produces reliable results.

1.5. RESEARCH QUESTIONS

To achieve the aim of this study, the following research questions have been formulated:

i. How large is the deviation in embodied carbon impacts between LOD 100/200 and LOD 300 for the same building?
ii. Which building elements drive the greatest share of the deviation between LOD levels, and how does the contribution of different component groups (structure, envelope, and interiors) compare across the assessed Levels of Development?
iii. Can certain component groups be considered negligible in BIM-based LCA due to their consistently minor contribution to total embodied carbon?
iv. How do the findings of this study compare with existing BIM-LCA research conducted at different Levels of Development?

1.6. SCOPE AND LIMITATIONS

The object under investigation is based on a prototype building developed by the Arbeitsgemeinschaft für zeitgemäßes Bauen e.V. (ARGE), as presented in Construction Research Report No. 80 from March 2021 [30]. The building in question is a detached single-family home. The model is developed according to the Level of Development (LOD) Specification, utilising the basic LOD definitions developed by the American Institute of Architects (AIA), with the focus on LOD 100, 200, and 300 developed by BIMForum [31]. Furthermore, the focus is on embodied carbon; therefore, the assessment covers only the A1–A3 stages of the LCA, representing the production stage on a cradle-to-gate basis.

The results of this case study are useful for comparison with previous research and cannot be generalised to all building typologies. Furthermore, LOD transitions involve modelling decisions that may introduce subjective variation.

1.7. STRUCTURE OF THE THESIS

The thesis is structured into seven chapters as follows:

Chapter 1 introduces the background and context of the study, outlining the climate relevance of embodied carbon in the building sector and the role of Building Information Modelling (BIM) in supporting Life Cycle Assessment (LCA). It presents the research motivation, problem statement, aim of the study, research questions, and the scope and limitations that define the boundaries of the investigation.

Chapter 2 reviews the theoretical foundation of embodied carbon and Life Cycle Assessment (LCA) in buildings. It covers global greenhouse gas emissions and the role of the building sector; the distinction between embodied and operational carbon; key carbon-intensive materials and reduction strategies; and the LCA methodology as governed by the ISO 14040/14044 framework, EN 15978, and EN 15804. It concludes by situating LCA within the German regulatory context, including the BNB and DGNB certification systems and the Ökobaudat database.

Chapter 3 addresses Building Information Modelling and its integration with LCA. It defines BIM according to ISO 19650, discusses its mandate within the German federal construction sector, and introduces the concept of Level of Development (LOD), distinguishing it from Level of Detail. The chapter closes with a discussion of BIM-LCA integration workflows, quantity takeoff mechanisms, and the software tools used in this study, Autodesk Revit and One Click LCA.

Chapter 4 presents the state of the art, critically reviewing existing studies that link BIM model maturity to environmental assessment outcomes. It examines component-level contributions to deviation, methodological inconsistencies across literature, and identifies the research gaps that this thesis aims to address.

Chapter 5 details the methodology adopted for this study. It describes the research design, the case study building, and the BIM modelling process across LOD 100, LOD 200, and LOD 300. It further explains the LCA workflow implemented in One Click LCA, including calculation tool selection, LOD-to-design-stage mapping, system boundaries, and the building material mapping procedure, before concluding with a discussion of validity and limitations.

Chapter 6 presents the results and discussion. It provides an overall building-level comparison of Global Warming Potential (GWP) across the three LOD stages, followed by a detailed element-by-element comparison of building components. The chapter synthesises these findings across elements, benchmarks them against existing BIM-LCA literature and DGNB reference values and discusses the limitations and practical implications arising from the analysis.

Chapter 7 concludes the thesis with a summary of findings in relation to the four research questions, an outline of the study's contribution to the field, a discussion of its limitations, and recommendations for both practice and future research.

2

EMBODIED CARBON AND LIFE CYCLE ASSESSMENT IN BUILDINGS

2.1. CLIMATE CHANGE AND THE BUILT ENVIRONMENT

2.1.1. GLOBAL GREENHOUSE GAS EMISSIONS AND CLIMATE CHANGE

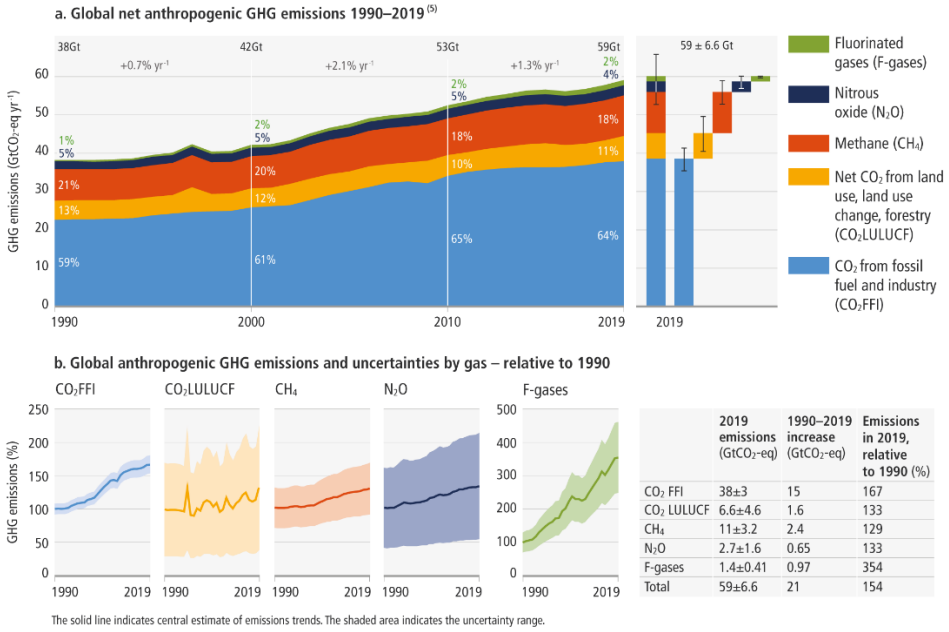
Over the past century, the concentration of carbon dioxide in the Earth's atmosphere has increased significantly. Scientific measurements have recorded an increase of more than 50% in CO_2 levels since the beginning of the industrial era in the 18th century [1]. The main gases contributing to the greenhouse effect are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and fluorinated gases (F-gases). These gases are essential because they trap heat from sunlight, warming the planet to a level that supports life. However, as the concentration of these gases increases, the Earth becomes progressively warmer. Since 1750, not only has CO_2 increased substantially, but the concentration of CH_4 has also grown by 156% and N_2O by 23% [5].

Carbon dioxide is a vital component of the atmosphere. It is released through both natural processes, such as wildfires and volcanic eruptions, and human activities, such as the burning of fossil fuels and deforestation. Methane also originates from both natural and human-caused sources. Natural sources include the decomposition of organic matter, landfills, rice farming, livestock digestion, and manure, while human-caused sources include leaks from fossil fuel production and transportation. Nitrous oxide primarily comes from agricultural practices and is released during the use of both commercial and organic fertilisers [5].

The IPCC has reported that average annual GHG emission levels for the decade from 2010 to 2019 were the highest ever recorded for each greenhouse gas. Combined annual GHG emissions grew by approximately 9 $GtCO_2$-eq yr^{-1} compared to the 2000–2009 decade, reaching 56 $GtCO_2$-eq yr^{-1} [3], [4]. The World Meteorological Organisation (WMO), through its Global Atmosphere Watch (GAW) programme, reported that in 2023 the three major greenhouse gases CO_2, methane (CH_4), and nitrous oxide (N_2O) all reached new record high concentrations. [5].

In line with the rising greenhouse gas concentrations reported by the IPCC, the organisation has also stated that each of the last four decades has been successively warmer than any preceding decade since the mid-19th century. The global surface temperature in the period 2011–2020 reached 1.1°C above the 1850–1900 baseline [3], [4]. This warming trend was further confirmed by the WMO's State of the Global Climate 2023 report, which recorded 2023 as the warmest year on record, with the global average near-surface temperature reaching 1.45°C above pre-industrial levels [5]. The IPCC attributes this temperature increase to unsustainable human energy use, land use, and consumption patterns. Furthermore, the consequences extend beyond rising air temperatures; oceans are warming, ice sheets and glaciers are

retreating, snow cover is decreasing, sea levels are rising, and extreme weather events are becoming increasingly frequent [3], [4], [5].



	2019 emissions ($GtCO_2$-eq)	1990–2019 increase ($GtCO_2$-eq)	Emissions in 2019, relative to 1990 (%)
CO_2 FFI	38±3	15	167
CO_2 LULUCF	6.6±4.6	1.6	133
CH_4	11±3.2	2.4	129
N_2O	2.7±1.6	0.65	133
F-gases	1.4±0.41	0.97	354
Total	59±6.6	21	154

Figure 1 - Global net anthropogenic GHG emissions (GtCO2-eq yr-1) 1990–2019 [32]

2.1.2. THE ROLE OF THE BUILDING SECTOR

According to the latest IPCC Sixth Assessment Report, the building sector was responsible for 21% of global GHG emissions in 2019. Of these, 57% were indirect CO_2 emissions from the off-site generation of electricity and heat, 24% were direct CO_2 emissions produced on-site, and the remaining 18% were embodied emissions primarily associated with the production of carbon-intensive materials, particularly cement and steel. Considering CO_2 alone, the building sector accounts for approximately 31% of global CO_2 emissions. Furthermore, buildings were responsible for 31% of global final energy demand and 18% of global electricity demand in 2019. Taken together, these figures confirm that the building sector is one of the largest contributors to planet-warming greenhouse gas emissions globally. Strikingly, the IPCC observed that global CO_2 emissions from buildings grew by 50% between 1990 and 2019 [3]. In addition, the building sector is responsible for approximately 40% of natural resource depletion and 25% of global waste generation [33].

These figures are particularly concerning in light of future population growth projections. According to the United Nations World Population Prospects, the global population is projected to rise from 8.1 billion in 2024 to approximately 10 billion by 2050 [34]. To meet the demands of this growing population, the global building stock is estimated to double in floor area by 2050, meaning that the construction decisions made today will determine building-related emissions for decades to come [35]. The Global Buildings Climate Tracker (GBCT) indicates that the building sector is considerably off course to achieve its decarbonisation targets for both 2030 and 2050 [11], [35]. Moreover, the AEC sector is considered one of the least digitalised industries, continuing to rely heavily on traditional practices and making limited investments in research and development, which contributes significantly to its slow productivity growth [24].

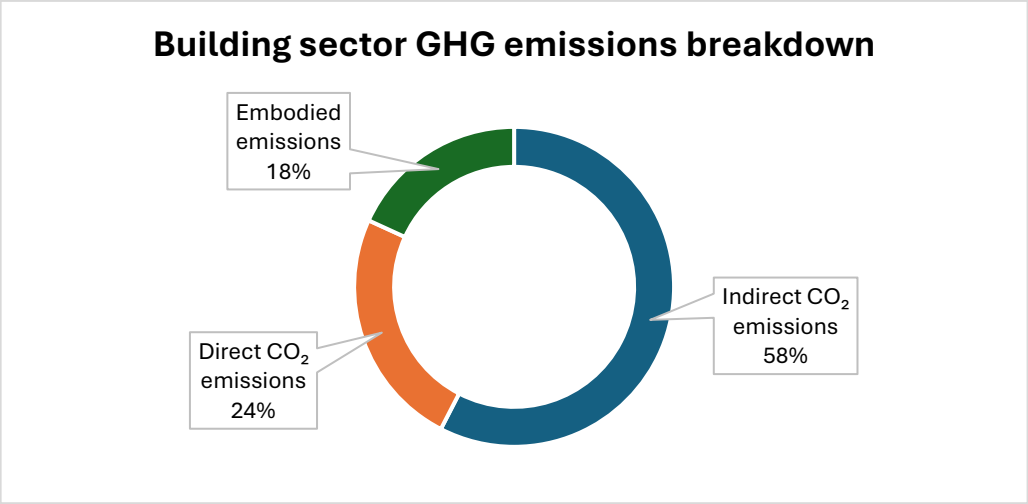


Figure 2 - Building sector GHG emissions breakdown

Despite the scale of the challenge, the building sector possesses one of the greatest mitigation opportunities among all sectors. According to the IPCC, it is possible to mitigate up to 8.2 $GtCO_2$-eq, representing approximately 61% of global building sector emissions by 2050, compared to baseline scenarios. Buildings have the potential to approach net-zero GHG emissions by 2050 if appropriate policy packages combining efficiency, sufficiency, and renewable energy measures are effectively implemented [3], [4]. Recognising this potential, governments and international organisations have responded with a range of policies and regulatory frameworks aimed at accelerating the decarbonisation of the built environment.

2.1.3. POLICY AND REGULATORY RESPONSE

The Paris Agreement is a legally binding international climate change accord, adopted on 12 December 2015 at the UN Climate Change Conference (COP21) in Paris, France, by 195 Parties, and entered into force on 4 November 2016. As of January 2026, the Agreement has 194 Parties. Its central objective is to limit the increase in global average temperature to well below 2°C above pre-industrial levels, while pursuing efforts to limit it to 1.5°C. Under this framework, each Party is required to submit a Nationally Determined Contribution (NDC), a national climate action plan that includes both mitigation targets aimed at reducing emissions and adaptation strategies to address the impacts of climate change [6]. Despite progress in updating these contributions, countries' collective commitments remain insufficient to limit global warming to either 1.5°C or 2°C, highlighting the need for considerably more ambitious action [4].

The European Green Deal, introduced in 2019, is the European Union's comprehensive strategy to address climate change and transition its economy toward a competitive, resource-efficient, and sustainable model [7]. It promotes a clean transition across the energy, transport, and industrial sectors, with the overarching goal of achieving climate neutrality by 2050. The European Climate Law (Regulation EU 2021/1119) makes this target legally binding, while also establishing intermediate targets of at least a 55% reduction in net greenhouse gas emissions by 2030 and a proposed 90% reduction by 2040, compared to 1990 levels [36]. Together, these instruments provide the regulatory framework ensuring that all EU economic sectors contribute to a carbon-neutral future. In line with these commitments, the EU submitted its updated NDC to the UNFCCC in 2025, reinforcing its climate neutrality goal for 2050 [8].

The revised Energy Performance of Buildings Directive (EPBD, Directive EU 2024/1275) forms a central pillar of the EU's regulatory framework for decarbonising the building sector [15]. It requires all new buildings to meet the Zero-Emission Building standard by 2030 and by 2028 for public buildings, prohibits on-site fossil fuel combustion in new buildings, promotes the phase-out of fossil-fuel heating systems, and, critically, introduces mandatory whole life-cycle Global Warming Potential (GWP) assessments for new buildings from 2028 onwards [15], [26]. This marks a significant regulatory shift where the EPBD historically focused almost exclusively on operational energy performance; it now explicitly addresses embodied carbon for the first time. At the national level, Germany's Gebäudeenergiegesetz (GEG) the Buildings Energy Act, regulates the energy efficiency of buildings, with its most recent revision requiring that newly installed heating systems generate at least 65% of their heat from renewable energy sources [37]. Taken together, these regulatory developments signal a clear transition toward whole life-cycle carbon accounting in the built environment, underscoring the growing importance of embodied carbon assessment, which is the focus of the following sections.

2.2. EMBODIED CARBON IN BUILDINGS

2.2.1. DEFINING EMBODIED AND OPERATIONAL CARBON

From a life cycle perspective, building-related GHG emissions comprise both operational and embodied components. Operational emissions arise during the use phase and maintenance of a building. They are primarily associated with the energy consumed to maintain indoor comfort levels — including heating, cooling, ventilation, lighting, and electrical appliances. At present, operational emissions still dominate, contributing approximately three-quarters of total life cycle emissions from buildings. Historically, the majority of policy focus and industry progress in the sector has been directed toward reducing operational emissions, driven largely by the transition to renewable energy and stricter building energy performance standards [9].

Embodied emissions, by contrast, are associated with the extraction and processing of raw materials, the manufacture of construction products, transport, on-site construction, maintenance and replacement of components, and end-of-life processes such as demolition, recycling, incineration, and landfill [17]. Currently, embodied emissions account for approximately 25% of total building sector GHG emissions [9].

Addressing the full climate impact of buildings therefore requires a whole life carbon approach, one that accounts for both operational and embodied emissions across the entire life cycle, from material extraction through to end-of-life [11]. Neither component can be considered in isolation, as reductions in one area may be offset by increases in the other. A comprehensive understanding of both is essential for making informed, low-carbon design decisions in the built environment. This makes early design decisions critically important for reducing total life cycle emissions.

2.2.2. THE GROWING IMPORTANCE OF EMBODIED CARBON

As operational energy efficiency improves and electricity grids decarbonise through renewable energy, operational carbon emissions from buildings are declining. This means embodied carbon is becoming a proportionally larger share of total life cycle emissions. Embodied carbon is unique because, unlike operational carbon, it cannot be retrofitted away once a building is built; it is locked in from the moment of construction [9]. In contrast to operational carbon, which can be reduced through future renovations and renewable energy adoption, embodied carbon becomes permanently embedded in the building once construction is completed, making early-stage design the only opportunity to address it.

Currently, embodied carbon accounts for approximately 25% of total building sector emissions — but this is projected to rise to nearly 49% by mid-century [11]. This means that upfront carbon associated with materials production and construction will be responsible for approximately half of the entire carbon footprint of new construction between now and 2050 [9]. With the global building stock expected to double in floor area by 2050, the cumulative embodied carbon from new construction represents a major and growing threat to the remaining global carbon budget [35]. Recognising this urgency, the World Green Building Council has called for a 40% reduction in embodied carbon from new construction and infrastructure by 2030 [9].

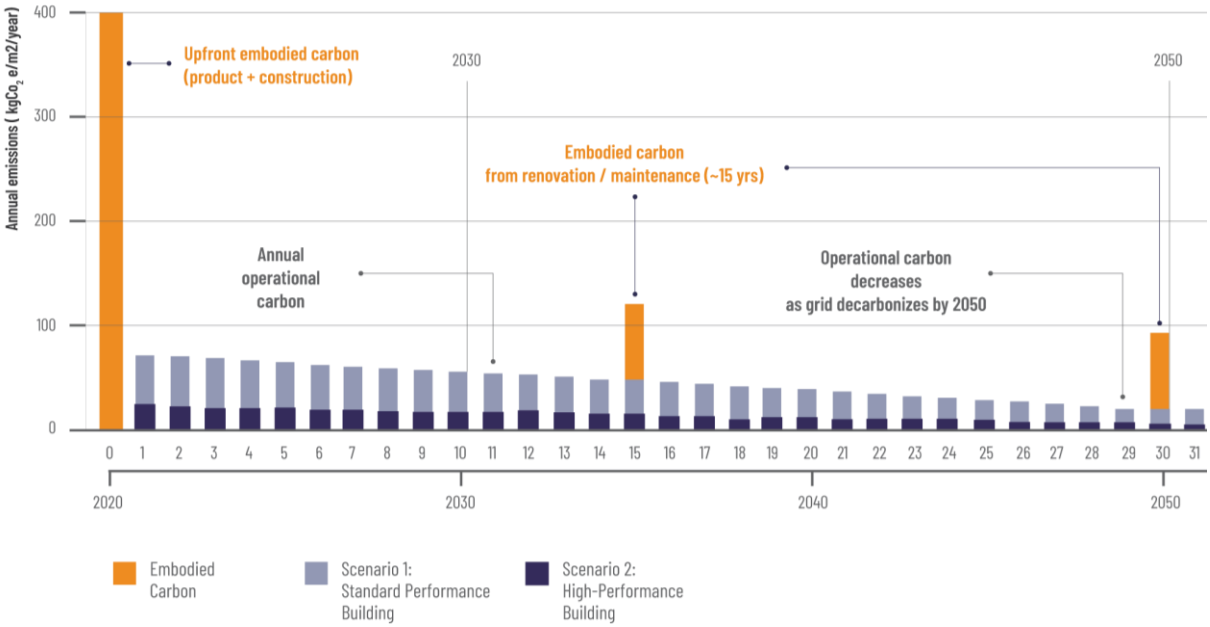


Figure 3 - Projected Impact of Embodied Carbon Relative to Operational Carbon (2020-2050) [13]

In highly energy-efficient buildings such as nearly zero-energy buildings (nZEBs) embodied carbon already dominates total life cycle emissions. Studies show that in new energy-efficient residential buildings, embodied impacts can represent around 50% or more of total GHG emissions over a 50-year lifetime [13], [38]. This shift is already observable in studies of highly efficient building typologies, where the operational contribution has become so small that embodied emissions dominate the entire life cycle profile. This evidence confirms that as operational energy requirements become increasingly stringent, embodied carbon will progressively determine a building's overall climate impact. Consequently, the three most carbon-intensive construction materials concrete, steel, and aluminium are now at the centre of decarbonisation efforts in the built environment, as discussed in the following section.

2.2.3. KEY MATERIALS AND REDUCTION STRATEGIES

The manufacturing of building materials is the single greatest contributor to embodied carbon in buildings. Among all construction materials, cement and steel are the most carbon-intensive, together accounting for approximately 11% of global CO_2 emissions. Cement production, which is essential for concrete manufacturing, is responsible for approximately 7% of global carbon emissions, primarily due to the energy-intensive clinker production process (source needed). Steel is the second most widely used

construction material globally, with emissions from the iron and steel industry accounting for approximately 7.2% of global GHG emissions. Together with aluminium, these three materials are the largest contributors to embodied carbon in the building sector, and as global urbanisation and construction activity continue to grow, reducing their carbon impact will be critical for achieving climate targets [3], [14]

Three main strategies have been identified for reducing embodied carbon in building materials: Avoid, Shift, and Improve. The Avoid strategy focuses on reducing material consumption through circular economy principles including reuse, recycling, material-efficient design, and extending building lifespans. Retrofitting and reusing existing buildings is preferable to demolition and new construction, as it distributes embodied carbon over a longer service life and avoids the upfront emissions associated with new material production. The Shift strategy encourages replacing carbon-intensive materials with low-carbon and renewable alternatives, including timber, bamboo, and earth-based materials. The Improve strategy aims to decarbonise conventional materials through electrification of manufacturing processes, increased use of renewable energy, carbon capture technologies, and greater use of recycled content — particularly for cement and steel. Together, these three approaches can substantially lower embodied carbon emissions while supporting the transition to a net-zero built environment [39].

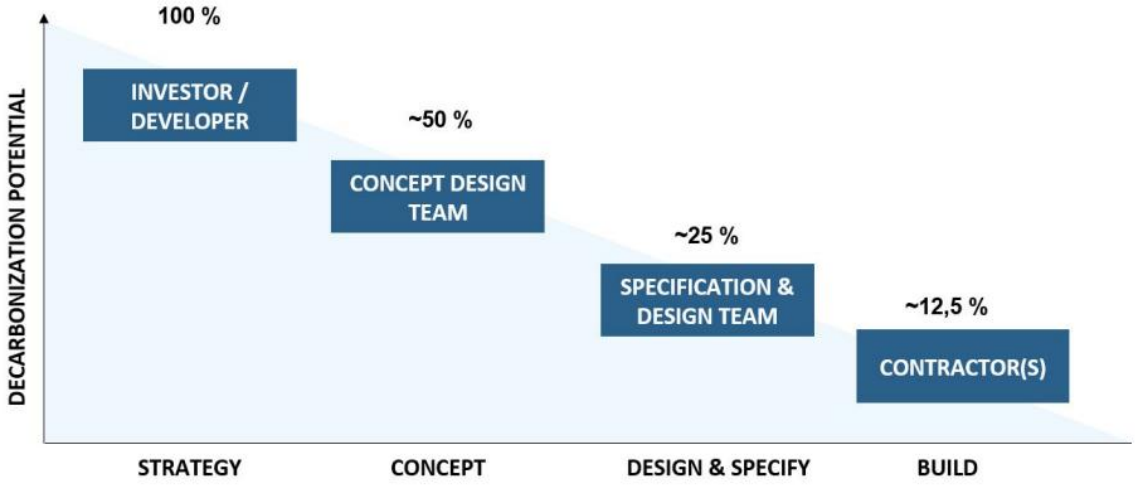


Figure 4 - Decarbonization potential throughout the building design and construction process [40]

Addressing embodied carbon in isolation is insufficient; a whole life-cycle approach is essential for effectively decarbonising the built environment. Life Cycle Assessment (LCA) evaluates environmental impacts across all stages of a building's life, from raw material extraction and manufacturing through to construction, operation, maintenance, and end-of-life reuse or recycling [41]. This approach enables decision-makers to account for both embodied and operational carbon simultaneously, supporting informed material selection and design choices. Furthermore, whole life cycle thinking supports circular economy principles by considering how materials can be recovered and reused as valuable resources at the end of a building's service life. Before any reduction strategy can be effectively implemented, embodied carbon must first be accurately measured and quantified. Life Cycle Assessment is the internationally recognised methodology for this purpose and is introduced in detail in the following section.

2.3. LIFE CYCLE ASSESSMENT (LCA)

2.3.1. LCA METHODOLOGY AND ISO FRAMEWORK

LCA originated in the 1960s in response to emerging concerns regarding environmental pollution and the scarcity of energy and raw materials. A pioneering 1969 study commissioned by Coca-Cola, comparing beverage containers, is widely recognised as one of the first major applications of the life cycle approach. During the 1970s and 1980s, methodological development expanded across the United States and Northern Europe, though these early studies remained largely uncoordinated and focused primarily on material and energy accounting. In the 1990s, the scientific community began international harmonisation efforts, culminating in the publication of the ISO 14040 series in 1997, which established the globally recognised framework still in use today. This foundation was further consolidated in 2006 with the release of the revised ISO 14040 and ISO 14044 standards, which serve as the analytical backbone for modern environmental assessment and policy [42].

LCA is defined as "a tool to assess the potential environmental impacts and resources used throughout a product's life cycle, i.e., from raw material acquisition, via production and use stages, to waste management" (ISO, 2006). This approach, commonly described as cradle-to-grave, evaluates the entire lifespan of a product, accounting for all resources consumed, emissions released, and waste generated at every stage. ISO 14040:2006 and ISO 14044:2006 are the foundational international standards governing the conduct of a Life Cycle Assessment. Published by the International Organisation for Standardisation, they function together as a comprehensive methodological framework for measuring the environmental footprint of a product, service, or process. ISO 14040 establishes the principles and framework, while ISO 14044 specifies the requirements and guidelines for conducting and reporting an LCA study [16], [41].

Life Cycle Assessment consists of four interlinked and iterative phases: goal and scope definition, life cycle inventory analysis (LCI), life cycle impact assessment (LCIA), and interpretation (ISO, 2006). The goal and scope definition phase establishes the study's purpose, defines the system boundaries, and selects a functional unit to serve as the quantified performance reference for all inputs and outputs. The LCI phase involves the systematic compilation and quantification of material and energy flows, as well as environmental releases, throughout the product's life cycle. During the LCIA phase, these inventory results are evaluated for their environmental significance, typically by translating them into impact indicators such as Global Warming Potential (GWP), expressed in kg CO_2-equivalent. Finally, the interpretation phase synthesises findings from the preceding stages to identify significant issues, conclude, and formulate recommendations. Because LCA is inherently iterative, findings from later phases frequently inform revisions to earlier decisions, ensuring that the final results are both comprehensive and internally consistent [41], [43].

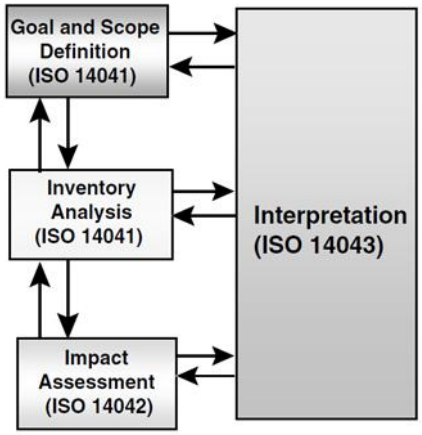


Figure 5 - Phases of LCA according to ISO 14040:2006 [41]

Unlike many other industrial processes, which typically involve a limited number of standardised elements with short lifespans, buildings incorporate a wide variety of products and components with long service lives and unique characteristics. Furthermore, building construction takes place in uncontrolled environments and is subject to external factors and multiple stakeholder decisions. As a result, performing a conventional LCA for buildings can be particularly complex and time-consuming. Practitioners face significant challenges in collecting Life Cycle Inventory (LCI) data, conducting Life Cycle Impact Assessments (LCIA), and interpreting results in a meaningful way. To address these challenges, dedicated international and European standards have been developed to guide building-specific LCA practice, as discussed in the following section. As part of mandate M/350, the European Committee for Standardisation (CEN) introduced a comprehensive framework of sector-specific standards, with EN 15978 addressing building-level assessments and EN 15804 governing environmental declarations for construction products [18], [44].

2.3.2. BUILDING-SPECIFIC LCA: EN 15978 AND EN 15804

As part of mandate M/350, the European Committee for Standardisation (CEN) developed a comprehensive framework of sector-specific standards, with EN 15978 addressing building-level environmental assessment and EN 15804 governing environmental declarations for construction products. Together, these two standards form the regulatory backbone of building LCA practice in Europe, providing a structured and sufficient methodological framework to address the specific complexity of buildings [45].

EN 15978 establishes a calculation method for evaluating and reporting the environmental performance of buildings using a life cycle assessment approach. The standard defines the object of assessment as the entire building, including its foundations and external works located within the site boundary, throughout its complete life cycle. To facilitate assessment, the building life cycle is organised into a series of information modules grouped into four main stages. The Product Stage (A1–A3) covers raw material extraction, transportation to the manufacturing facility, and product manufacturing. The Construction Process Stage (A4–A5) covers transportation to the construction site and the installation of products into the building. The Use Stage (B1–B7) addresses operational and maintenance activities, including repair, replacement, refurbishment, operational energy use, and operational water consumption. The End-of-Life Stage (C1–C4) encompasses deconstruction, transportation, waste processing, and final disposal. In addition, Module D accounts for the potential environmental benefits

and loads associated with reuse, recovery, and recycling beyond the building's system boundary. The standard adopts the building's required service life as the default reference study period, ensuring that long-term impacts such as operational energy use and component replacements are consistently considered over a comparable timeframe [17], [46].

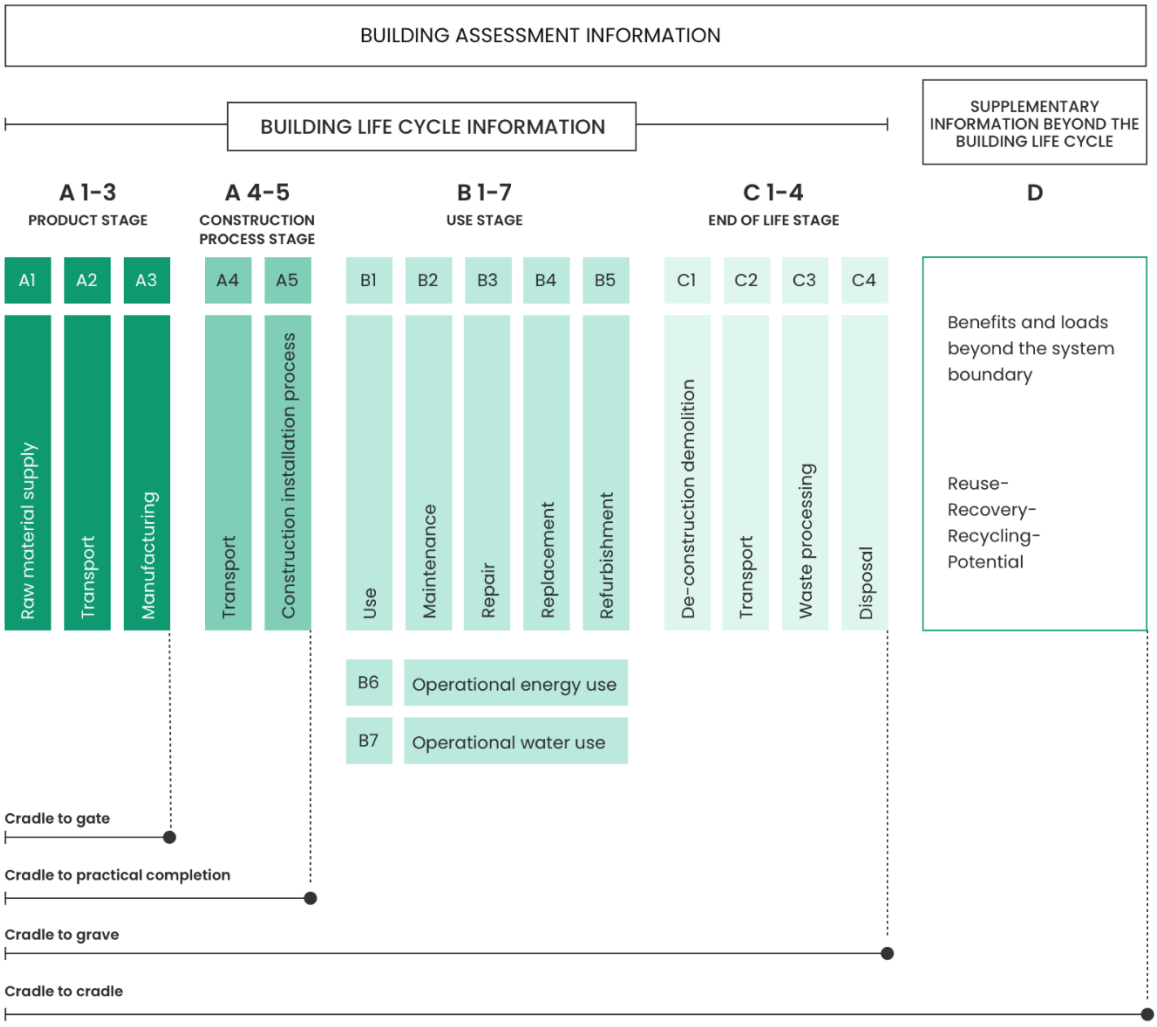


Figure 6 - Life cycle stages and information modules for building environmental assessment according to EN 15978 [17]

EN 15804 provides the core product category rules (PCR) for developing Type III Environmental Product Declarations (EPDs) for construction products and services. Its purpose is to ensure that environmental information is generated using a consistent and verifiable LCA-based methodology, enabling it to be used reliably in building-level assessments conducted under EN 15978. At minimum, the standard requires EPDs to declare environmental impacts for modules A1–A3, C1–C4, and Module D, while additional life cycle modules may be included depending on the product type and the scope of the declaration. The revised version, EN 15804:2012+A2:2019, was subsequently adopted in Germany as DIN EN 15804:2022 and introduced additional mandatory environmental impact indicators and strengthened

alignment with the European Commission's Product Environmental Footprint (PEF) framework [18]. These updates enhanced the consistency and comparability of EPD data across different manufacturers and geographical regions [17], [47].

EN 15978 and EN 15804 are closely interlinked and are designed to be applied together. Building-level assessments conducted in accordance with EN 15978 rely on the environmental data provided through EPDs developed under EN 15804 as their primary input [47]. In practice, the environmental impact of a building is determined by multiplying the quantities of each construction product used by the corresponding environmental impact values reported in their EPDs. These results are then aggregated across the relevant life cycle modules to determine the overall environmental performance of the building [46], [47]. Consequently, the reliability of a building LCA is directly dependent on the quality, completeness, and representativeness of the EPD data used as input. This makes EPD databases a critical component of building life cycle assessment, and a key factor influencing the accuracy of environmental evaluations, an aspect explored in detail in the following section.

2.3.3. ENVIRONMENTAL PRODUCT DECLARATIONS (EPDS) AND DATABASES

An Environmental Product Declaration (EPD) is a standardised and independently verified document that provides quantified information about the environmental impacts of a product or service throughout its life cycle, based on life cycle assessment methodology. EPDs are classified as Type III environmental declarations according to ISO 14025, which distinguishes them from other environmental labels by requiring transparent reporting of LCA results and independent third-party verification, rather than compliance with predefined performance thresholds. Within the construction industry, EPDs are prepared by manufacturers in accordance with the requirements of EN 15804, which establishes the product category rules (PCR) for construction products and services (DIN EN 15804, 2022). The verification and publication process is overseen by programme operators such as the Institut Bauen und Umwelt (IBU) in Germany and the Building Research Establishment (BRE) in the United Kingdom, ensuring that all declarations comply with the relevant standards before being made publicly available [18], [44].

EPDs present environmental information based on a declared unit, commonly defined as one kilogram, one cubic metre, or one square metre of a product, and clearly specify the life cycle stages included within the system boundary (DIN EN 15804, 2022). Environmental impacts are quantified using a set of mandatory indicators required by EN 15804+A2:2019, including Global Warming Potential (GWP), Ozone Depletion Potential (ODP), Acidification Potential (AP), Eutrophication Potential (EP), Photochemical Ozone Creation Potential (POCP), and Abiotic Depletion Potential for both elements and fossil resources (ADPE and ADPF) (DIN EN 15804, 2022). At a minimum, EPDs must declare environmental impacts for the Product Stage (A1–A3), the End-of-Life Stage (C1–C4), and Module D. Additional modules may also be included depending on the characteristics and life cycle of the product. These environmental impact values constitute the primary source of input data for building-level life cycle assessments conducted in accordance with EN 15978 and therefore represent a fundamental component of building LCA calculations [48].

To support the application of building life cycle assessment, EPD data is collected and distributed through dedicated digital databases that provide access to verified datasets from a wide range of manufacturers and programme operators. In Germany, ÖKOBAUDAT is the most widely used database, maintained by the Federal Ministry for Housing, Urban Development and Building (BMWSB). It contains both manufacturer-specific EPDs and generic datasets supporting environmental assessments within certification systems such as the DGNB and BNB [49]. At the European level, ECO Portal serves as a centralised platform that aggregates EPDs from numerous national programme operators, improving the accessibility and comparability of construction product data across different countries (ECO Platform,

2023). Other important sources of environmental data include the INIES database in France and the IBU Data portal in Germany. In addition, software platforms such as One Click LCA and SimaPro integrate multiple databases, enabling practitioners to access a broad range of environmental datasets within a single assessment environment [47], [50].

Although the availability of EPD data has increased significantly in recent years, several challenges remain regarding data quality and representativeness. A key concern is geographical relevance, as EPDs developed for products manufactured in one country may not accurately reflect the production processes, energy mix, or supply chains applicable in another region (DIN EN 15804, 2022). Differences in reference years also affect comparability, as older EPDs may not account for technological improvements or updated environmental characterisation factors. In cases where product-specific EPDs are unavailable, practitioners often rely on generic or proxy datasets from sources such as ÖKOBAUDAT or ecoinvent, which can introduce additional uncertainty into the assessment results. Consequently, the reliability of a building LCA depends strongly on the selection of appropriate and representative datasets, and on the transparency with which data sources, assumptions, and limitations are documented throughout the assessment process [51].

2.3.4. LCA IN THE GERMAN CONTEXT

Germany has played a pioneering role in integrating life cycle assessment into building policy. The publication of the first ÖKOBAUDAT database in 2006, followed by the introduction of the first sustainability certification systems in 2008, positioned Germany among the earliest countries to formally incorporate LCA into sustainable construction governance. This development has been largely coordinated by the Federal Ministry for Housing, Urban Development and Building (BMWSB), which embedded LCA principles within the Leitfaden Nachhaltiges Bauen, the federal guideline governing the sustainable construction, operation, and refurbishment of publicly funded buildings (BMWSB, 2019). In recent years, the role of LCA has become increasingly prominent. The introduction of the Klimafreundlicher Neubau (Climate-Friendly New Building) funding programme in 2022 requires project developers seeking financial support to demonstrate compliance with specified life cycle greenhouse gas emission thresholds through a building LCA. This progression reflects Germany's broader policy shift away from a focus primarily on operational energy efficiency towards a comprehensive evaluation of environmental impacts across the entire building life cycle [52], [53].

The Bewertungssystem Nachhaltiges Bauen (BNB) serves as the official sustainability assessment and certification framework for federal buildings in Germany and is administered by the BMWSB (BMWSB, 2024). Within this system, life cycle assessment represents a core quantitative evaluation method used to measure environmental performance across a building's life cycle stages. Assessments are conducted in accordance with EN 15978 and rely exclusively on datasets provided through ÖKOBAUDAT (BMWSB, 2024). The BNB framework evaluates a range of environmental impact categories, with particular emphasis placed on Global Warming Potential (GWP) due to its direct relevance to climate change mitigation. By prescribing both the assessment methodology and the source of environmental data, the BNB framework establishes a consistent and comparable basis for evaluating environmental performance across federal building projects. As a result, it provides a standardised approach for integrating LCA into public-sector construction planning and decision-making [52], [53], [54].

ÖKOBAUDAT serves as Germany's official database for life cycle assessment data in the construction sector and is maintained by the BMWSB. The database contains a broad range of datasets, including manufacturer-specific EPDs and generic datasets covering construction materials, transportation processes, energy supply, construction activities, and end-of-life scenarios. All current datasets comply with the requirements of EN 15804+A2, ensuring methodological consistency across environmental assessments. As the mandatory data source for BNB assessments and a widely used reference within

DGNB certification projects, ÖKOBAUDAT has become the primary source of environmental data for building LCA in Germany. Its compatibility with a range of assessment tools and software platforms has further reinforced its position as the core data infrastructure supporting environmental evaluation within the German construction industry [53]

In addition to the publicly administered BNB framework, the Deutsche Gesellschaft für Nachhaltiges Bauen (DGNB) operates Germany's most widely recognised private-sector building certification system. Since its introduction in 2009, DGNB certification has gained significant national and international recognition and is widely regarded as one of the most comprehensive sustainability assessment schemes available [55]. Life cycle assessment is embedded within the DGNB assessment methodology and contributes approximately 13.5% of the total certification score. With more than 200 certified projects annually, the DGNB system has played an important role in promoting the practical application of LCA across the German construction sector [56]. Supporting this ecosystem is the Institut Bauen und Umwelt (IBU), Germany's primary EPD programme operator, which develops and publishes environmental product declarations in accordance with EN 15804 and collaborates with more than 400 manufacturers from Germany and abroad [57]. Collectively, the BNB, DGNB, ÖKOBAUDAT, and IBU constitute a well-established institutional framework that has positioned Germany as a leading example in the systematic implementation of building life cycle assessment.

One aspect of building life cycle assessment that often receives insufficient attention is the generation of reliable material quantities, commonly referred to as quantity take-off. These quantities form the basis of environmental impact calculations, as they are directly combined with the environmental impact values obtained from EPD datasets. Consequently, the accuracy of a building LCA depends not only on the quality of the environmental data used, but equally on the precision and completeness of the material quantities incorporated into the assessment. Errors or omissions in quantity data can significantly distort the final results, regardless of the quality of the underlying EPD datasets. The increasing adoption of Building Information Modelling (BIM) within the German construction industry offers a significant opportunity to improve this process by enabling the automated extraction of material quantities directly from digital building models [52]. The relationship between BIM-based quantity takeoff and building LCA therefore represents an important area of investigation and forms the basis of the following chapter.

3

BUILDING INFORMATION MODELLING AND BIM-LCA INTEGRATION

3.1. BUILDING INFORMATION MODELLING (BIM)

3.1.1. DEFINITION, PRINCIPLES, AND ISO 19650

According to ISO 19650-1, Building Information Modelling (BIM) is defined as the "use of a shared digital representation of a built asset to facilitate design, construction and operation processes to form a reliable basis for decisions" (DIN EN ISO 19650-1, 2019). In other words, BIM is a digital representation of a building's physical and functional characteristics, typically implemented as a 3D model that integrates geometric, technical, and performance data. It enables all project participants, designers, engineers, contractors, facility managers, and owners to access and share a common, structured information base throughout the building life cycle, thereby reducing coordination errors and improving communication across design, construction, and operation phases [58], [59]. In practice, BIM is realised through specialised 3D modelling and information management software such as Autodesk Revit, Bentley, Vico, or ArchiCAD, which provide "smart" object-based models rather than simple drawings [60], [61].

ISO 19650 is the international standard for information management in BIM. It establishes a structured framework for the consistent management of project and asset information throughout the asset life cycle. The standard defines information requirements, clarifies stakeholder roles and responsibilities, facilitates collaboration among project participants, governs information exchange within a Common Data Environment (CDE), and ensures the quality and reliability of information during both the delivery and operational phases [20], [62].

3.1.2. IN THE GERMAN CONTEXT (BIM DEUTSCHLAND, FEDERAL MANDATE)

Germany's construction sector is undergoing a significant digital transformation. In 2015, the Federal Ministry for Digital and Transport (BMDV) introduced the Stufenplan Digitales Planen und Bauen, a strategic, phased plan to drive the modernisation of the German construction industry through the gradual adoption of BIM. The plan was designed to provide all stakeholders with a clear understanding of the requirements and expertise needed to implement BIM effectively. In 2021, the use of BIM became mandatory for federal infrastructure projects and buildings as part of the public procurement process [62].

The German Federal Government established BIM Deutschland to support the digital transformation of the infrastructure and construction sector. This body offers a broad range of supporting measures, including education, advisory services, networking, and the promotion of shared understanding among all stakeholders. BIM Deutschland operates in alignment with the ISO 19650 standard and serves as a central reference point for BIM workflows in Germany [63].

In 2021, the German Federal Ministry for Housing, Urban Development and Building (BMWSB), together with the Federal Ministry of Defence (BMVg), published the Masterplan BIM für Bundesbauten to guide the implementation of Building Information Modelling (BIM) in federal construction projects. The document describes a step-by-step approach for introducing BIM throughout the building life cycle. BIM was first applied during the design phase in 2022, followed by its integration into construction management, and became mandatory for federal projects valued at over €0.5 million by 2025. The plan aims to achieve full digital integration of federal building projects by 2027. To support this process, the German BIM Implementation Strategy for Federal Buildings provides practical guidance by defining four organisational pillars and introducing twelve standardised implementation tools, including Employer's Information Requirements (EIR/AIA), to ensure a consistent openBIM procurement processs [63].

3.1.3. BIM ACROSS THE DESIGN AND CONSTRUCTION PROCESS

Within a BIM process, the modelling software is the central technological component, offering tools to define building elements, assemblies, materials, and systems while maintaining links between graphical objects and their associated non-geometric attributes (e.g. material type, quantity, performance data). Revit, for example, supports architectural, structural, and MEP modelling, handles complex geometries efficiently, and can import, export, and link data in common exchange formats, making it widely used for multidisciplinary coordination. 3D visualisation improves stakeholder understanding of the design, and the ability to store higher levels of detail in the model allows more accurate quantity take-offs, including reinforcement and other components [64].

BIM supports different functions at different project stages, including early design (massing and spatial planning), detailed design (component specification and coordination), construction (clash detection and scheduling), and facility management (operation and maintenance). According to the BIM Project Execution Planning Guide developed by Penn State University, 21 distinct Model Uses have been identified, organised by project phase from planning through design, construction, and operation, each requiring different levels of information and model content [65]. The level of information in the model grows progressively as the project advances. This progressive enrichment of the model is directly linked to the LOD concept, which will be discussed in Section 3.2.

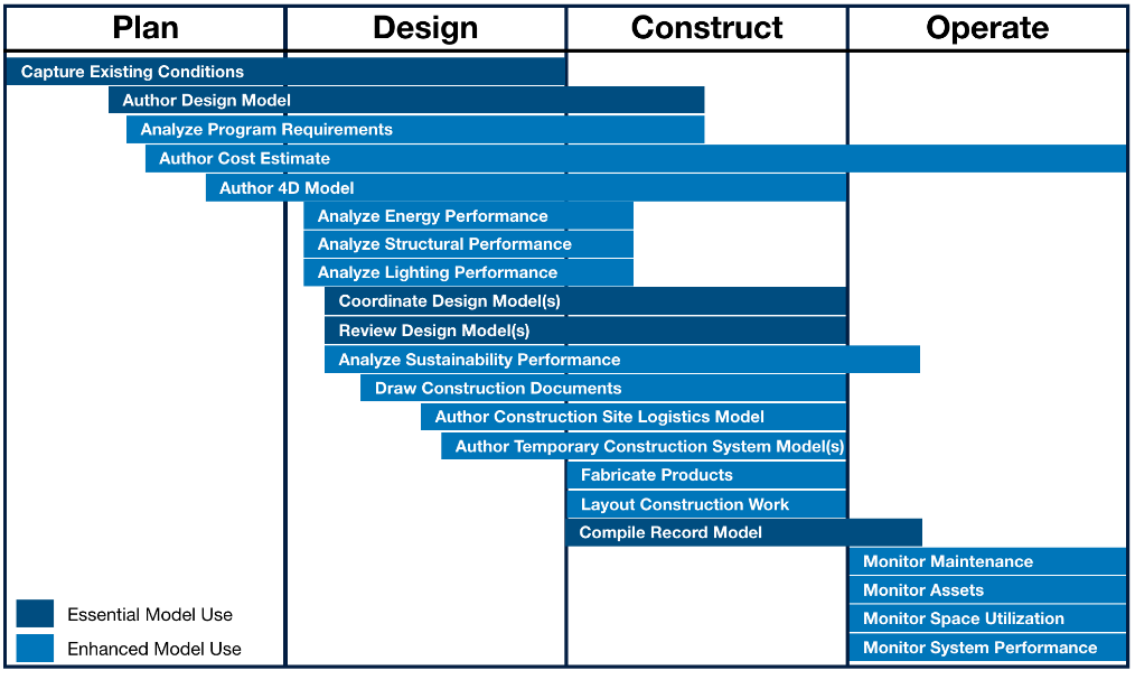


Figure 7 - Common Model Uses [65]

According to a global survey by buildingSMART International (2022), 85% of organisations use BIM primarily for 3D design coordination, and 72% for clash detection and quality checks, while applications such as cost estimation and facility management remain less consistently adopted. This variation in BIM use across project stages reflects the broader challenge of standardising model content and information maturity, a challenge that is formally addressed through the concept of Level of Development, discussed in the following section [66].

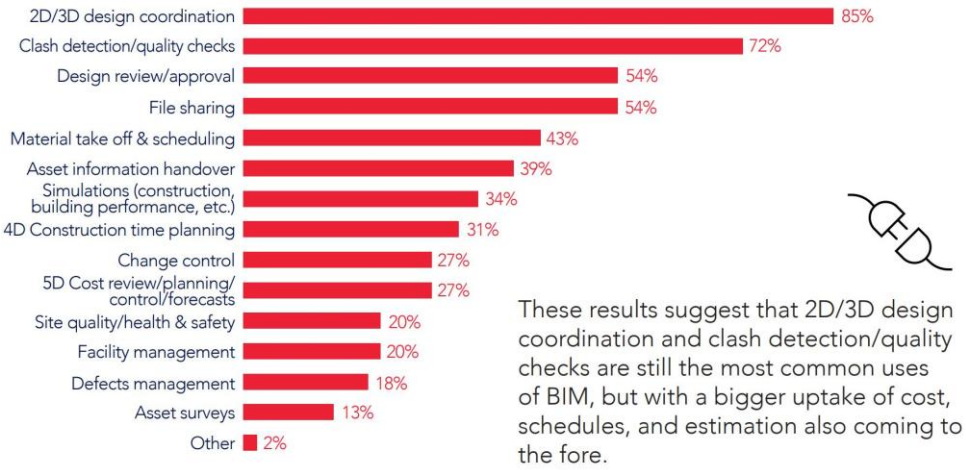


Figure 8 – Survey result of common uses of BIM [66]

3.2. LEVEL OF DEVELOPMENT (LOD)

3.2.1. DEFINITION AND CLASSIFICATION OF LOD

Level of Development (LOD) is a BIM concept used to specify how much information a model element contains and how reliable that information is at a given stage of a project. In the BIM-LCA literature, LOD is consistently described as a framework that structures model content progressively from low to high maturity, making it possible to relate the available BIM information to the type and accuracy of environmental assessment that can be carried out [24], [28], [67].

The origin of LOD is traced in the literature to early BIM standardisation efforts in practice rather than to LCA research itself. Ferreira et al. explain that the concept was initially introduced in 2004 as "level of detail" within the Model Progression Specification developed by Vico, and that it later evolved through the American Institute of Architects (AIA) classification system and related frameworks such as the UK PAS 1192-2. In the BIM-LCA papers, however, the most recurrent reference point is the AIA-based five-level structure, which organises LOD into the well-known sequence from 100 to 500 [28], [44], [67].

3.2.2. LEVEL OF DETAIL VS LEVEL OF DEVELOPMENT

Level of Development (LOD) is a BIM concept used to specify how much information a model element contains and how reliable that information is at a given stage of a project. In the BIM-LCA literature, LOD is consistently described as a framework that structures model content progressively from low to high maturity, making it possible to relate the available BIM information to the type and accuracy of environmental assessment that can be carried out [68].

While the terms Level of Detail (LoD) and Level of Development (LOD) are often used interchangeably, there are fundamental differences in their purpose and what they measure.

- **Level of Detail (LoD):** This concept originated in computer graphics to regulate the amount of detail used to represent a virtual world, primarily for balancing rendering performance with visual complexity. In the AEC industry, it describes the quantity of geometric detailing included in a model element [68]
- **Level of Development (LOD):** Introduced by the American Institute of Architects (AIA) in 2008, this concept builds upon LoD but shifts the focus to the completeness and reliability of information. It represents the degree to which an element's geometry and alphanumeric (semantic) information have been fixed and verified by the project participants [31]. When defining the Level of Development (LOD), a fundamental distinction is made between Level of Geometry (LOG), which specifies the geometric detailing of an element, and Level of Information (LOI), which specifies the required alphanumeric data [68].

The primary distinction lies in visual representation versus reliability:

- **Graphic Content vs. Maturity:** LoD is a visualisation-focused concept that describes how detailed an element looks. In contrast, LOD is a maturity indicator that determines the extent to which a project participant can rely on that information for further planning and decision-making.
- **Detail vs. Certainty:** An element can possess a high Level of Detail (e.g., LoD 400 with intricate shapes and MEP penetrations) while simultaneously being at a low Level of Development (e.g., LOD 100) if those details are not yet fixed and are likely to change.
- **Geometric vs. Semantic Split:** While both can involve geometric and alphanumeric data, LOD is specifically understood as a combination of Level of Geometry (LOG) and Level of Information (LOI), providing the meta-information necessary for collaboration between different disciplines [68].

The Level of Information Need (LOIN) is a newer European standard that specifies the exact geometric and semantic information needed at a particular design phase for a specific task and actor. Introduced in the EN 17412-1:2020 standard, LOIN provides a more flexible and purpose-driven framework instead of relying on predefined levels such as LOD. Unlike LOD's focus on individual element maturity, LOIN is use-case centred and avoids a fixed set of levels better to accommodate diverse information requirements for specific exchange scenarios [44], [68].

3.2.3. LOD IN PRACTICE LOD 100, 200, AND 300

The five LOD levels are described with slightly different wording across the papers, but their meaning is highly consistent. LOD 100 refers to a symbolic or highly simplified representation, where geometry is preliminary, and quantities are not yet clearly defined. LOD 200 introduces generic objects with approximate quantities, sizes, dimensions, locations, and orientations. At the same time, LOD 300 represents a more specific and measurable model in which key components and materials are identified with sufficient maturity to support more robust analysis. LOD 400 adds fabrication, installation, connection, and detailed material information, and LOD 500 corresponds to the as-built condition [64].

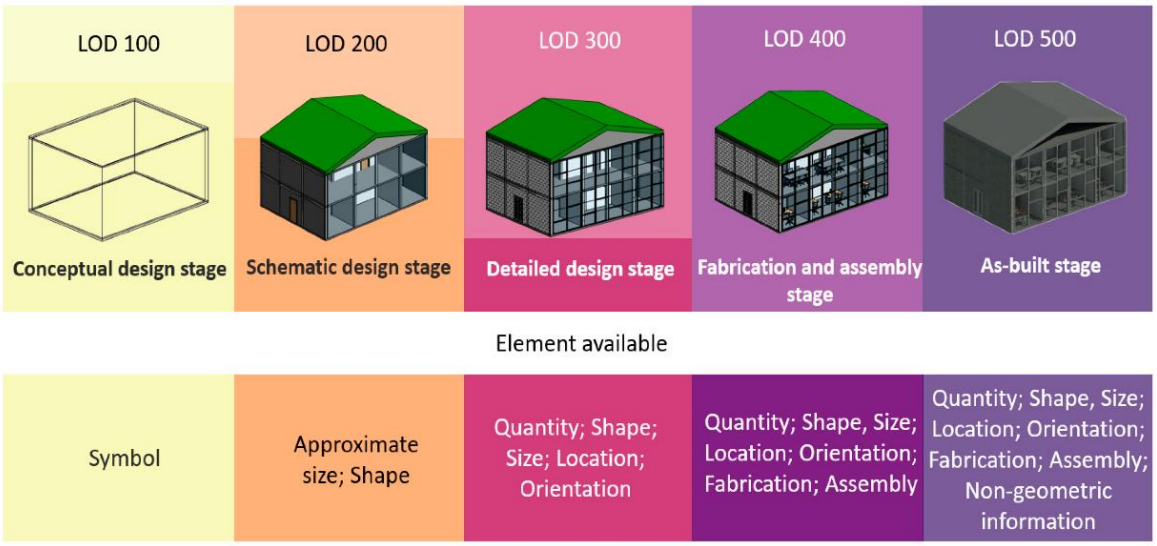


Figure 9 - Building elements in the BIM model under LOD 100-LOD 500. M model under LOD 100-LOD 500 [64]

Several papers also emphasise that intermediate levels may be used when the standard five thresholds are not sufficient to capture project maturity. Parece et al. note that levels such as LOD 350 can be used between the main thresholds[24]. Nilsen and Bohne describe LOD 350 as a stage where quantity, size, shape, location, and orientation can be measured directly from the BIM model, and the model can begin to support decision-making more reliably [69]. The present study focuses on LOD 100, 200, and 300, as these levels correspond to the early and detailed design phases where embodied carbon assessments are most impactful and where intervention is still feasible.

3.3. BIM-LCA INTEGRATION

3.3.1. FROM BIM MODEL TO ENVIRONMENTAL ASSESSMENT

Building Information Modelling (BIM) has been recognised as a promising enabler of environmental performance assessment because building models can store information on geometry, materials, components, and quantities. This makes BIM a useful starting point for life cycle assessment (LCA), since environmental evaluation depends on reliable inventory data that can otherwise require substantial manual collection and processing. In this sense, BIM can reduce the effort of quantity take-off and support earlier environmental assessment during the design process [29].

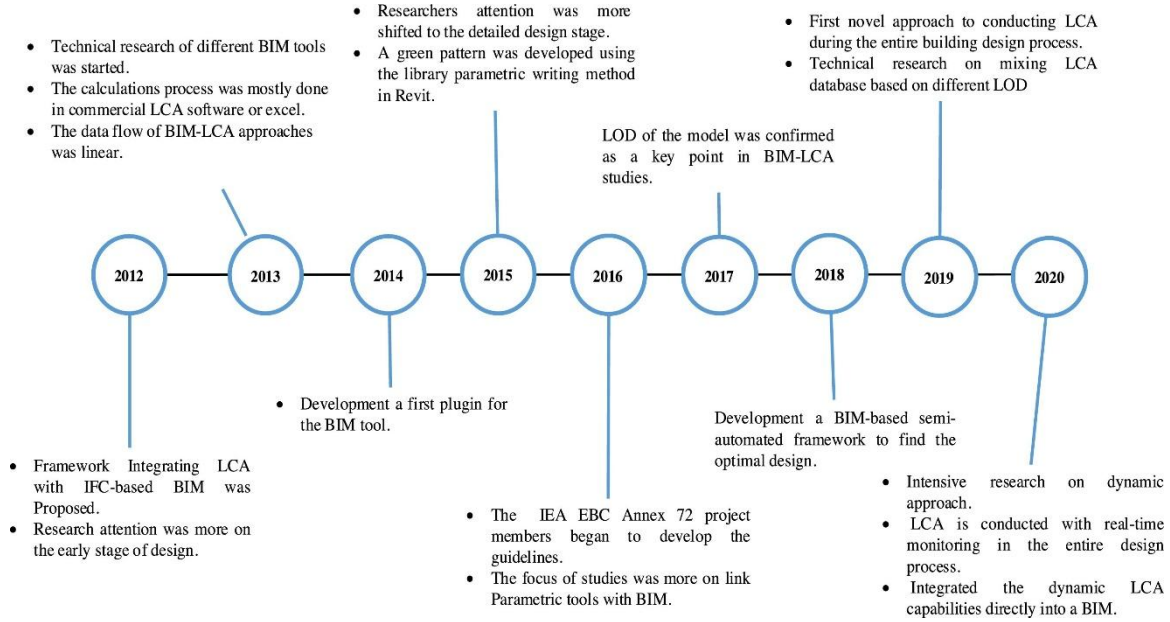


Figure 10 - Advances and development in the field of integrating BIM and LCA since 2012 [28]

However, the integration of BIM and LCA is still limited by data interoperability, inconsistent information structures, and the difficulty of translating model data into LCA-ready inputs. Recent studies note that although BIM can simplify data acquisition, the workflow is still often fragmented and dependent on manual checking, data mapping, or simplification assumptions. As a result, BIM-LCA integration is promising in principle, but its practical implementation remains constrained by technical and methodological gaps [29].

Generic design tools in BIM platforms are not always tailored to precise environmental analysis workflows, and using BIM together with spreadsheets or separate calculation tools for energy use and CO_2 emissions can become time-consuming. A critical bottleneck is the mapping between BIM material libraries (e.g. Revit's material list) and external LCA databases such as ecoinvent: naming conventions differ, many BIM materials are composites or loosely defined, and units (e.g. m^2, m^3 in BIM vs kg in LCI datasets) often do not match. Without careful mapping strategies and unit conversion, significant manual effort is required, which undermines the expected efficiency gains of BIM-based LCA and highlights the need for better interoperability between BIM environments and LCA data sources [70].

3.3.2. QUANTITY TAKEOFF AND DATA EXCHANGE

BIM–LCA integration can be implemented through several workflows, but the literature shows a common progression from manual data transfer toward more automated and dynamic exchange. Although different authors use different labels and grouping systems, most classifications describe similar mechanisms for connecting BIM models to life cycle assessment tools. These include exporting quantity data to spreadsheets or external LCA software, using interoperability formats such as IFC, applying

plugins within BIM environments, and more advanced approaches based on visual programming or embedded environmental data [64].

Huang et al. and Bolognesi et al. both distinguish between conventional, semi-automatic, and dynamic approaches, showing that the highest level of integration is not yet the most common in practice [22], [71]. Chen et al. focus more directly on the technical data exchange mechanism, identifying BOQ import, IFC import, BIM viewers, and plugin-based calculations as distinct workflows [64]. Across these studies, the main pattern is similar: the simpler workflows rely on exporting model information to external tools, while the more advanced workflows aim to keep environmental calculations closer to the BIM environment itself.

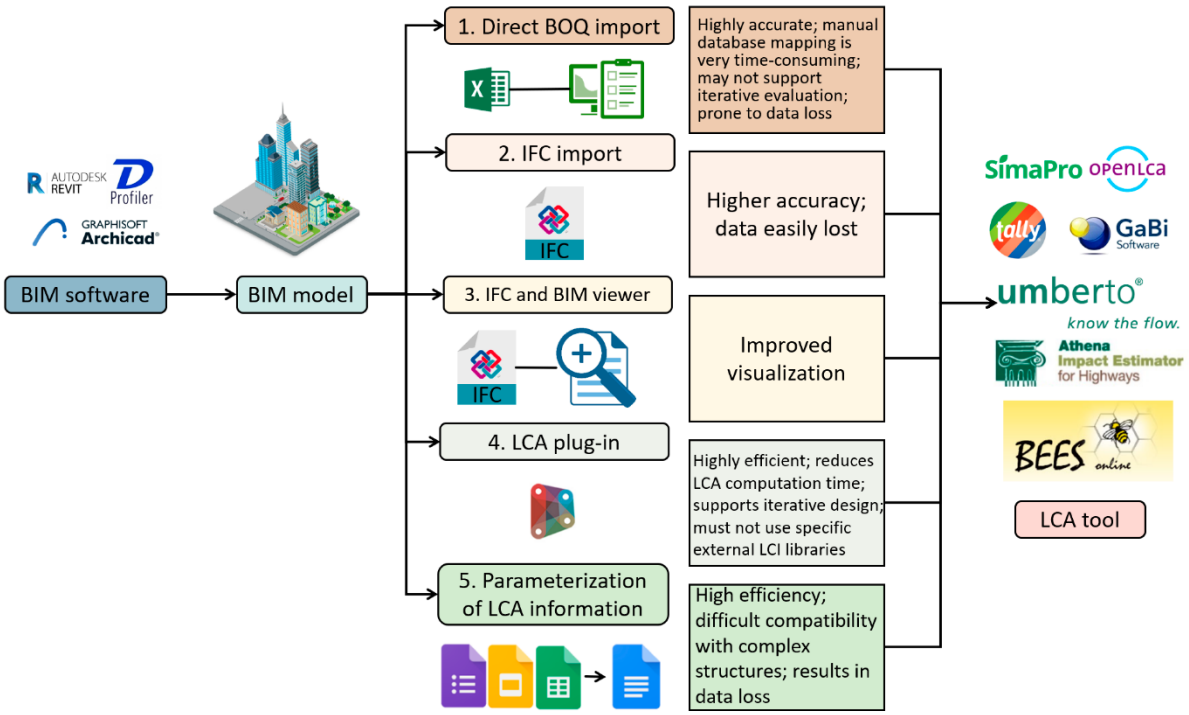


Figure 11 - BIM process integrated with LCA approach framework [64]

Despite this progress, a major bottleneck remains the translation of BIM data into LCA-ready information. Material libraries in BIM platforms do not always match LCA database structures, naming conventions differ, and units often need to be converted before environmental data can be applied reliably. In addition, BIM materials may be generic, composite, or only loosely defined, which creates a significant amount of manual checking and mapping. This reduces the efficiency gains expected from BIM-based LCA and shows that interoperability between BIM models and LCA databases is still an unresolved challenge [72].

3.3.3. SOFTWARE TOOLS REVIT AND ONE CLICK LCA

Autodesk Revit is one of the most frequently used BIM platforms in BIM-LCA workflows because it stores geometric, material, and component information that can be extracted for environmental assessment. The review by Chen et al. shows that Revit is commonly used as the BIM environment in integration studies, often because it supports 3D visualisation, quantity extraction, and links to external formats such

as Excel, IFC, and plugin-based workflows. In this way, Revit acts as the data source from which building information can be transferred into LCA tools for further processing [64].

One Click LCA is a cloud-based life cycle assessment platform for buildings and infrastructure that supports sustainability analysis, EPD generation, and compliance reporting. According to the company, it offers AI-powered LCA and EPD software, integrates with more than 20 BIM and other tools, supports more than 140 standards and methods, and provides access to more than 500,000 LCA and EPD data points. In Revit-based workflows, One Click LCA is used to receive model data or bill of quantities information, after which environmental impacts can be calculated and reported in a form suitable for design and compliance decisions [73].

Although this integration improves efficiency compared with fully manual assessments, it still depends on the quality of the underlying BIM model and the consistency of the mapping between model objects and LCA database entries. The main limitations remain material naming, unit conversion, and the need to verify that exported quantities correctly represent the modelled elements [64]. For that reason, Revit and One Click LCA should be presented as a practical workflow pair, rather than as a fully automated and error-free solution.

4

STATE OF THE ART

4.1. INTRODUCTION

Life Cycle Assessment (LCA) is increasingly recognised as an important decision-support method in the building sector, particularly during the early design phase, when the greatest number of design alternatives is still available, and modifications can be made with relatively low effort. Safari et al. highlighted that early-stage LCA is especially valuable because it informs design choices when flexibility is still high. Once the project progresses toward later stages, the range of feasible alternatives decreases, and conducting LCA only at the end of the design process becomes less useful because most major decisions have already been fixed. At the same time, the early design stage is also characterised by incomplete, uncertain, and often unreliable data, which makes the application of LCA more difficult and raises questions about the credibility of the results [28] .

A central issue in the literature is therefore the relationship between the maturity of the BIM model and the reliability of the environmental assessment. LCA studies can be performed at different Levels of Development (LOD), depending on the goal and scope of the study, yet only a limited number of publications have explicitly examined how LCA results vary across LODs. Safari et al. noted that many case studies in the literature do not clearly specify the LOD of the BIM model used for assessment[28]. In fact according to Parece et al., a systematic review found that 63% of the 115 articles analysed did not disclose the LOD. Moreover, only 15 articles performed LCA continuously throughout the design process, meaning that most of the articles performed LCA in a specific phase of the building process[24].

A narrow evidence base compounds this reporting gap. The literature exhibits a clear typological bias as low-rise residential and office buildings dominate the sample of case studies. In contrast, high-rise and structurally complex buildings such as hospitals or public facilities remain significantly underrepresented. This imbalance limits the generalizability of current findings across the broader spectrum of building typologies. Taken together, these observations, the lack of LOD reporting, the limited number of continuous studies, and the narrow typological scope, establish the central problem that this thesis addresses: the relationship between model maturity and the reliability of BIM-based LCA remains insufficiently understood and inconsistently documented [24].

4.2. LEVEL OF DEVELOPMENT

Few studies have attempted to quantify how environmental results change as BIM models become more detailed. Rezaei et al. compared LCA results at LOD 100 and LOD 300 and addressed early-stage uncertainty through probabilistic modelling using Monte Carlo simulation. Their main conclusion was that the LOD 300 result fell within the uncertainty range generated for the LOD 100 assessment. This

suggests that early-stage LCA can be considered reliable only when it is interpreted as a range of possible outcomes rather than as a single precise value. In other words, the deviation between early and later assessments may be acceptable if early-stage variability is properly represented [74].

A different perspective was provided by Hollberg et al., who analysed 34 weekly BIM states of a real office building project in Switzerland and tracked how embodied Global Warming Potential (GWP) evolved during the design process. Their study found that **embodied GWP during the early design phase could be as much as twice that of the final building.** This discrepancy was mainly attributed to modelling practices such as the use of placeholder materials, overlapping layers, quantity take-off errors, and incomplete information for technical building systems. Their results show that BIM-based LCA outputs generated from early design models can be misleading or even counterproductive if they are interpreted too literally, especially for approval procedures or major design decisions. However, an important limitation of Hollberg's study is that it did not explicitly use the LOD framework, even though it clearly dealt with progressive model development [29].

While Hollberg et al. reported that early-stage estimates were substantially higher than final ones, Nawrocka et al. found that models developed at LOD 200 produced GWP results that were 14.7% lower than those at LOD 400 [75]. These contrasting findings indicate that the effect of LOD on environmental performance depends not only on model maturity but also on regional construction practices, building typologies, modelling assumptions, and the environmental databases used in the background.

Among the most explicit attempts to structure the relationship between BIM development and LCA data is the framework proposed by Cavalliere et al. Their approach links each building element's LOD to an LCA database with a corresponding level of detail and allows different databases to be combined consistently across design phases. In this framework, LOD 100 is associated with average values assigned to whole building systems; LOD 200 uses average values for assemblies and introduces minimum and maximum ranges to represent uncertainty; LOD 300 relies on more specific component solutions; and LOD 400 moves toward material-level specificity. Cavalliere et al. reported that, with this approach, the environmental impact estimated in a given design phase remained within the variability range of the previous phase, allowing progressively narrower and more robust predictions as the project developed. At the same time, they acknowledged that mismatches can occur when components assumed in earlier phases do not exist in later stages or when database coverage is incomplete. Their work is particularly relevant because it offers a practical strategy for preserving comparability between design stages, unlike studies that compare snapshots without defining consistent data rules [67].

Ferreira proposed another important framework for early-stage BIM-LCA, but instead of relying strictly on fixed LOD categories, this work uses the concept of Level of Information Need (LOIN). The framework is purpose-driven and includes an intermediate early-design assessment stage, referred to as Level 2A, in which average Environmental Product Declarations (EPDs), derived from samples of 3, 5, or 10 EPDs, are used when specific products are not yet known. This stage is followed by a more detailed Level 2B, where specific EPDs are assigned. The method was implemented as a Revit plugin developed in C and connected to online EPD databases. It was validated through a case study of a real house in Portugal. The results showed that larger EPD samples reduced variability in early-stage results. Still, some impact categories, such as water depletion potential (WDP) and ozone depletion potential (ODP), remained too variable for robust early averaging. This study is particularly important because it addresses reliability directly by quantifying the difference between generic-data and specific-data assessments and by showing that uncertainty depends strongly on data quality, sample size, and indicator selection rather than only on geometric maturity [44].

Table 1 - Summary of key studies on LOD-related deviation in BIM-based LCA

Author	Content
Rezaei [74]	Compares LOD 100 vs LOD 300 by running LCA at both stages and handling early-stage unknowns probabilistically (Monte Carlo). Their key result is that "the impact of the LOD 300 stage is within the range of uncertainty of the LOD 100 LCA," meaning LOD 100 can be "reliable" only in the sense of giving a range that later detailed results fall inside, not a single precise value.
Hollberg [29]	This paper conducted an automated BIM–LCA workflow on 34 weekly BIM states of a real building and found that the embodied GWP "during the design phase is twice as high as for the final building," largely because designers use placeholder materials that are refined later.
Cavalliere [67]	Proposes a way to keep results consistent across phases by linking each element's LOD to an LCA database with a matching level of detail and mixing databases consistently. With that approach, they report that "the environmental impact in a certain design phase is always within the range of variability of the previous phase," enabling progressively tighter predictions toward the completed project result, while also noting mismatches can occur when components present in early assumptions are absent later or when database coverage is limited.
Ferreira [44]	Proposes a purpose driven BIM–LCA framework based on LOIN rather than fixed LOD, including an intermediate early-design LCA step ("Level 2A") that uses average EPDs (averaged from 3/5/10 EPDs) when specific products are unknown, then transitions to a detailed step ("Level 2B") using specific EPDs; implemented as a Revit plugin (C language) connected to online EPD databases and validated with a real house case study in Portugal, comparing early-average vs later-specific results and showing that larger EPD samples reduce variability. Still, some indicators (e.g., WDP/ODP) remain too variable for robust early averaging.

Despite these contributions, none of the studies above examines which specific building elements are responsible for the deviation observed between LOD stages; they report only aggregate, whole-building deviation. This distinction matters, since a deviation driven by structural elements would carry different implications for decision-making than one driven by finishes or technical systems.

A further limitation across this body of work concerns the transition from design-stage models to as-built conditions. Safari noted that while early-stage LCA is useful for decision-making, assessments should be continuously updated as the design evolves. However, there have been few comparisons between LOD 300, where the design is largely complete, and LOD 500, where the building reflects as-built conditions after construction [28]. This represents an important gap because the real environmental performance of a project ultimately depends on what is actually built, not only on what was modelled during design.

4.3. LINKING MODEL MATURITY TO ENVIRONMENTAL DATA

Taken together, these studies show that the reliability of early-stage BIM-LCA depends on more than the graphical maturity of the model. It is also shaped by the quality of the environmental data, the way uncertainty is represented, the quantity take-off method, and the consistency of assumptions between phases. Santos, for example, suggested that LOD 300-350 can be considered a realistic reference point for accurate and sufficiently complete LCA calculations [76]. In contrast, LOD 200 is more appropriate for screening or simplified assessments supported by external databases of typical construction solutions. At such early stages, practitioners usually rely on approximate quantities and generic datasets, which increases uncertainty and reduces precision [24]. For this reason, the relationship between LOD and data quality is especially important for decision-making, since it determines how confidently alternative design options can be compared.

This distinction between screening, simplified, and complete LCA is also reflected in the EeBGuide Handbook, which classifies LCA applications according to the purpose of the assessment, the availability of data, the project's state of development, and the practitioner's expertise. The handbook distinguishes three broad application types: Screening LCA, Simplified LCA, and Complete LCA [24], [28]. This classification is useful because it suggests that not every design stage requires the same level of detail or precision. Instead, the expected accuracy of the assessment should align with the project's maturity and the decision context in which the LCA is used.

Another major theme in the literature concerns the type and source of environmental data linked to BIM objects. Generic and specific EPDs are often used at different moments in the design process depending on the availability of product information. Different studies also rely on different databases for the life cycle inventory step, which complicates comparisons between methods and case studies [24], [28]. Cavalliere et al. explicitly addressed this issue by proposing a framework that combines different databases according to design phase and object maturity [67]. Similarly, Mohamed et al. used average ICE database values at lower levels of development and EPD-based data at more advanced stages [77]. Palumbo et al. argued that even in LOD 100-200 stages, EPDs should be preferred over fully generic data whenever possible, provided that safety factors and statistical descriptors such as minimum, maximum, average, and median are used to reflect variability within product groups [78].

Several authors have therefore proposed structured strategies for linking BIM elements with external environmental data sources. Ansah et al. used predefined families, types, and BIM templates for prefabricated elements [79]. Parece et al. proposed that, for early design and approximately LOD 200, material quantities and average GWP values should be stored in an external catalogue of building assemblies. At the same time, BIM elements are connected to this information through construction classification codes. This approach enables the creation of hierarchical LCA databases in which functions are broken down into systems and systems into materials [24]. Similar strategies were presented by Arvizu-Piña et al. for exterior walls using a Mexican database of standard construction systems, and by Li et al., who also used classification systems to connect building components to predefined material groups in external databases [80], [81].

A related strategy is to enrich BIM models with embedded knowledge repositories that contain technical and environmental information suitable for early-stage assessment. Forth et al. and Schneider-Marin et al. proposed linking materials to functional layers and assigning environmental impacts using ÖKOBAUDAT data. Experts then combine these materials into generic building components and define acceptable thickness ranges for each layer [82], [83]. Rezaei et al. followed a similar logic by first assessing materials with the Ecoinvent database and then assembling them into construction systems linked to BIM objects [74]. These approaches show that early-stage BIM-LCA often depends on externalised knowledge structures that compensate for the lack of detailed design information inside the model itself.

The practical performance of these predefined-component and classification-based approaches has also been evaluated. Soust-Verdaguer established correspondences between IfcBuildingElement classes and the BCCA cost database structure to estimate quantities for each element, concluding that this method could capture approximately 89% of material volume through quantity take-off and around 60% of total impacts during early design [84]. By contrast, Hansen et al. found that predefined components at early stages may underestimate total environmental impacts by roughly 12% on average when compared with detailed design results [85]. These findings underline that such methods are useful for approximation and decision support, but they still entail a non-negligible degree of uncertainty.

4.4. COMPONENT-LEVEL CONTRIBUTION TO DEVIATION

While the previous section showed that LOD strongly influences aggregate LCA results, it did not clarify which specific building elements drive these deviations. This distinction is important because different component groups mature at different rates during design, and their contribution to overall uncertainty may vary accordingly. According to Hollberg, walls, slabs, mechanical equipment, and ducts were among the main contributors to embodied impacts, while other studies also confirmed the major role of walls [29]. Kiamili similarly reported that HVAC systems can account for between 15% and 36% of total life cycle emission [86].

However, these findings describe which elements contribute most to total impact, not which elements are responsible for the deviation between LOD stages specifically. This is a meaningful gap: an element could have a large total impact but a small LOD-related deviation if it is modelled with reasonable accuracy even at early stages. In contrast, another element could have a smaller total impact but a much larger deviation if it is poorly represented in early design (for example, technical systems that are typically underdefined until later phases). None of the reviewed studies addresses this distinction directly.

At the same time, some authors noted that the environmental indicators considered should reflect regional priorities, since different countries may face different environmental pressures; for example, water scarcity may justify stronger emphasis on water-related indicators in some Asian contexts. This suggests that both element contribution and indicator selection should be adapted to the assessment context.

4.5. METHODOLOGICAL INCONSISTENCIES

Beyond data structure and modelling detail, several authors have also discussed methodological inconsistencies in BIM-LCA studies. Functional units vary widely across the literature, with many studies using the complete building as the reference unit even though a building consists of multiple components that serve different functions and may be more appropriately assessed through distinct units. Moreover, occupancy and space use are often not considered, even though they can influence environmental performance. Most case studies assume a reference service life of 50 years, but system boundaries differ significantly depending on the scope of the study. System boundary definition is a critical methodological decision in LCA calculation, as it determines the overall scope of what a study includes and excludes [24], [28]**.**

System boundary definition is a particularly critical methodological decision, as it determines the overall scope of what a study includes and excludes. Studies vary widely in which building systems they include within their boundaries. Some studies incorporate heating, ventilation, and air conditioning systems, finding that ducts and pipes are major contributors to embodied impacts. Others expand further to include broader technical equipment such as electrical systems, lighting, plumbing, mechanical equipment, and fire safety devices, yet still exclude transportation to the construction site, operational

energy consumption, and water use from their scope. Transportation-related impacts are particularly inconsistent across the literature, even though transport distances between material production and construction sites vary significantly by geographic location and should, in principle, be factored in. In practice, researchers often rely on industry-average data or omit this stage entirely due to limited access to accurate figures. Similarly, the repair and refurbishment phase receives even less attention than other life cycle stages across the reviewed studies [24], [28].

Several studies adopt a fairly comprehensive scope covering most life cycle stages, but still exclude specific elements, such as operational water use, waste processing, or the use phase itself. Others exclude transportation, operational energy, and water use entirely, while some omit the end-of-life phase altogether due to insufficient data. Several studies settle on a "complete" LCA covering four core stages: production, construction, use, and end-of-life, while excluding demolition and reuse. In contrast, at least one study extended its boundary specifically to examine how different materials and energy consumption patterns affect embodied emissions across the full life cycle, explicitly incorporating reuse, recycling potential, and landfill outcomes. Other studies adopt a two-tiered approach, offering both a simplified analysis limited to material production and a more comprehensive analysis when additional data becomes available [24], [28].

These three methodological choices, functional unit, service life, and system boundary, are rarely justified explicitly in the reviewed literature. Instead, they appear to be selected based on data availability and convenience rather than a principled rationale tied to the study's specific goal. This inconsistency makes direct comparison between studies difficult, since no shared standard governs which parameters or life cycle stages should be included, and it further complicates the interpretation of LOD-related deviations discussed in the previous sections, **since a deviation observed between two studies may reflect differing system boundaries or functional units just as much as differing model maturity.**

4.6. RESEARCH GAPS AND FUTURE DIRECTIONS

Building on the methodological inconsistencies discussed above, the modelling maturity of BIM data and the quality of LCA tools both play a pivotal role in result accuracy and in the effectiveness of BIM-LCA integration overall. Some literature reviews reported that only a relatively small number of studies explicitly document the LOD of the BIM model used [28]. Hollberg and Cavalliere also suggested that engineers and designers do not necessarily work with LOD formally or explicitly during everyday design practice, even though their workflows clearly involve changing levels of information detail [67]. This discrepancy between academic frameworks and professional practice reinforces the need for methods that are both rigorous and practical. Identifying the main sources of uncertainty and integrating them explicitly into BIM-LCA workflows may therefore lead to more robust and transparent results.

Parece also observed that many literature reviews on BIM-LCA were published before 2022 and that fewer comprehensive review studies have appeared afterward [24]. This suggests that, despite rapid methodological development, the field still lacks updated syntheses that consolidate recent advances and remaining challenges. In that sense, a current state-of-the-art review remains necessary, particularly regarding how LOD, data quality, uncertainty, and environmental databases interact in early-stage assessment.

Overall, the literature shows that early-stage BIM-LCA is both necessary and inherently uncertain. Existing approaches have attempted to address this uncertainty through predefined families, external catalogues, hierarchical databases, classification-based links, average or range-based environmental values, and probabilistic methods. These strategies resemble simplification approaches used in early energy modelling, where approximate indicators such as surface area may replace more detailed volumetric representations. Although they improve feasibility and comparability, robust BIM-LCA

integration still depends on consistent data structures, semantic compatibility, and transparent assumptions, whether implemented through proprietary BIM tools or interoperable schemas such as IFC.

Despite the progress achieved so far, an important research need remains: a clearer and more standardised relationship between model maturity and the type of LCA application being performed, whether screening, simplified, or complete. There is also a need to understand better how quantities and environmental results change between design stages so that correction factors, estimation rules, or adjustment methods can be developed for use in early-stage models. This is especially relevant for screening-level assessments, where missing information is unavoidable and where practitioners must still make decisions despite limited certainty.

Beyond these near-term needs, a further research direction concerns using machine learning to strengthen early-stage BIM-LCA workflows. One possibility is to train predictive models on previous projects so that probable material assignments can be generated automatically based on parameters such as building type, geometry, and function. Another possibility is to predict environmental indicators directly from simplified early-design parameters, such as building form, number of storeys, and intended construction system, without requiring fully specified material definitions. This could support faster estimation of GWP or embodied energy during concept design. However, the feasibility of such approaches depends strongly on the availability of sufficiently large datasets containing as-built BIM models linked to verified LCA outcomes [24].

In this respect, recent initiatives such as the Built Environment Carbon Database suggest that progress is being made toward shared data resources that may support future data-driven approaches [87]. In parallel, BIM-LCA tools capable of recording environmental performance continuously throughout the design process could generate longitudinal datasets suitable for more advanced machine learning applications, including recurrent neural networks for temporal modelling and graph neural networks for learning relationships between building elements and recurring material assemblies. Generative artificial intelligence methods, such as GANs and diffusion models, may also support early design exploration by proposing environmentally optimised configurations. Although these developments are still emerging, they point toward a future in which BIM-LCA becomes more adaptive, predictive, and informative during uncertain early design stages [24].

In summary, this review identifies four key gaps in the current literature. **The present study directly addresses the first two gaps; the remaining two are acknowledged as important but fall outside its scope.**

- Inconsistent or absent LOD reporting across the BIM-LCA literature, limiting comparability between studies **(addressed)**
- Lack of element-level analysis of LOD-driven deviation, with existing studies reporting only aggregate, whole-building deviation **(addressed)**
- Limited comparison between design-stage models (LOD 300) and as-built conditions (LOD 500) **(not addressed in this study; noted for future research)**
- Underdeveloped standardisation linking model maturity to the appropriate type of LCA application **(partially relevant, depending on final scope)**

5
METHODOLOGY

5.1. RESEARCH DESIGN

This study adopts a comparative single-case-study design to investigate how inconsistencies in Level of Development (LOD) influence the outcomes of Building Information Modelling (BIM)-based Life Cycle Assessment (LCA). A single residential building was selected and modelled three times in Autodesk Revit, once at LOD 100, once at LOD 200, and once at LOD 300, following the definitions established by the BIMForum LOD Specification. By holding the building itself constant and varying only the level of model development, LOD is treated as the independent variable. At the same time, the resulting differences in LCA outcomes represent the dependent variable of interest. This design directly supports the research objective introduced in Chapter 1, namely, to determine how model maturity affects the reliability of embodied carbon assessments during early design stages.

A single-case comparative design was chosen because it allows tight control over confounding variables that typically complicate cross-study comparisons in BIM-LCA research. Since all three models represent the same building, with identical geometry, location, materials, and structural system, any observed variation in LCA results can be attributed specifically to differences in LOD rather than to differences between buildings. This addresses a further gap identified in the state-of-the-art review (Chapter 4): existing BIM-LCA studies are inconsistent in which LOD standard they follow or fail to specify one at all. Rezaei et al. and Hollberg et al. reference LOD stages descriptively without citing a defining standard, while Cavalliere et al. and Ferreira et al. explicitly ground their LOD definitions in the AIA classification system or its successors, such as PAS 1192-2 and the EN 17412-1 LOIN framework, rather than the BIMForum specification [29], [44], [67], [74] . This lack of a shared reference point makes it difficult to compare LOD-related findings across studies with confidence. By explicitly adopting the BIMForum LOD Specification [31] as the defining standard for all three models in this study, the design ensures internal consistency and reproducibility, even though this focus on a single case limits the generalisability of the findings beyond the specific building studied.

The remainder of this chapter details how this comparative design was implemented in practice. Section 5.2 describes the case study building selected for this analysis. Section 5.3 explains the modelling process used to develop the three Revit models at LOD 100, 200, and 300. Section 5.4 outlines the LCA workflow carried out using One Click LCA, including the assumptions kept constant across all three models. Section 5.5 describes the method used to compare and analyse the resulting LCA outputs, and Section 5.6 discusses the validity and limitations of this approach.

5.2. CASE STUDY DESCRIPTION

The building under investigation is based on a prototype single-family home developed by the Arbeitsgemeinschaft für zeitgemäßes Bauen e.V. (ARGE), as documented in Construction Research Report No. 80. ARGE has operated since 1946 as a central research and consulting network for the construction sector in Northern Germany and is recognised as a federal construction research institution and the Institute for Rationalisation in Schleswig-Holstein, focusing on testing, implementing, and ensuring the quality of contemporary construction methods and materials. This type building was derived by ARGE from statistical data, market observations, and demand-oriented analyses of single-family home construction in Germany, providing a representative and transferable basis for practice-related studies [30]

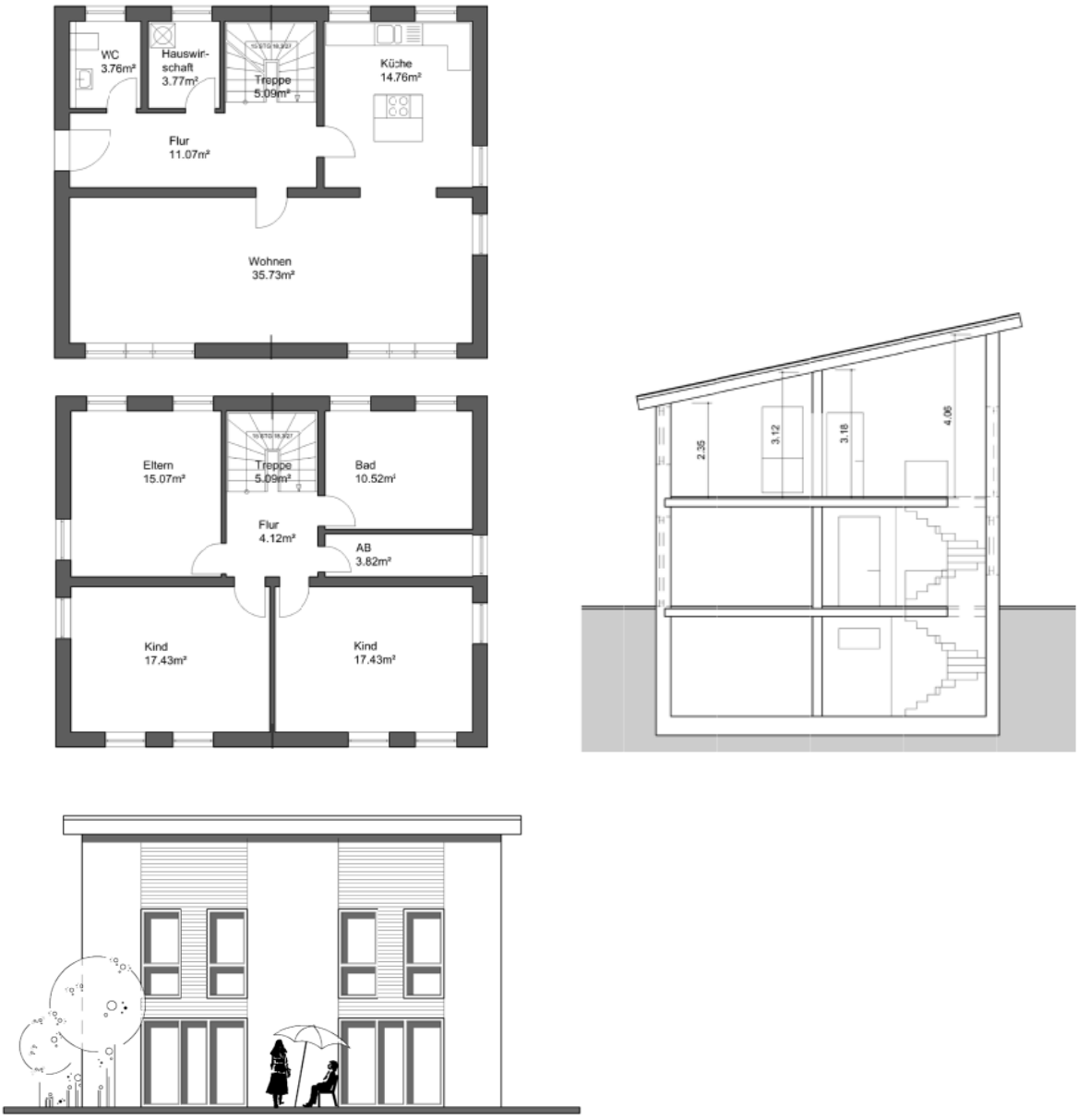


Figure 12- Floor plans, section, and front elevation of the case study building [30]

The building comprises a single detached residential unit with four to five living rooms across a living area of approximately 146 m^2, a heat-transferring envelope area of approximately 421 m^2, and a heated building volume of approximately 560 m^3, resulting in an A/Ve ratio of 0.75, which is typical for single-family houses. It is constructed in the medium quality segment, with a basement level, a mono-pitch roof, two full storeys, and an internal staircase [30].

The building follows a load-bearing wall construction system rather than a beam-column frame, consistent with common practice for German single-family residential buildings. The primary vertical structure is formed by the external walls and a share of internal load-bearing walls, while the horizontal structure consists of concrete floor slabs spanning between these walls. External walls have a total thickness of 370 mm and were modelled with an External Insulation and Finish System (EIFS), while internal load-bearing walls were modelled as typical German masonry construction with a representative thickness of 17.5 cm. The foundation and basement walls were modelled in concrete, with rigid insulation applied to the foundation walls. The floor slabs and internal staircase were both modelled as reinforced concrete, consistent with common construction practice for this building type. The roof was modelled as an insulated timber rafter construction, comprising a tile covering, a wood fibreboard sub-layer, 160 mm of rock wool thermal insulation, an 80 mm timber joist/rafter structural layer, and an internal gypsum board finish.

Table 2 - Building elements and material construction of the case study building

Element	Material (layers, outer to inner)
External wall system	Masonry with EIFS (External Insulation and Finish System)
Internal load-bearing walls	Masonry
Internal non-load-bearing walls	Metal (steel) stud partition
Basement wall	Concrete with rigid insulation
Foundation	Concrete
Floor slabs	Reinforced concrete
Staircase	Reinforced concrete
Roof system	Insulated timber rafter construction
Door	Timber/wood or PVC frame with solid/panel leaf
Windows	Aluminium frame with double

The ARGE type building was selected as the case study for this research because it provides a validated, representative single-family home design rather than an arbitrary or hypothetical building. Since the prototype was derived from statistical data, market observations, and demand-oriented analyses of single-family home construction across Germany [30], it reflects common building practice rather than a design specific to one architect or project, which supports the generalisability of the findings to typical German residential construction. Furthermore, the building's moderate size and load-bearing wall construction system made it practical to model consistently across three distinct LOD stages (100, 200, and 300), since it was neither too simple to demonstrate meaningful differences in model maturity nor too complex to model reliably within Revit at each stage. This combination of a validated reference design and a manageable scope for repeated modelling made the ARGE type building particularly well

suited to isolating the effect of LOD progression on LCA outcomes, which is the central objective of this study.

5.3. BIM MODELLING PROCESS

5.3.1. INTRODUCTION

To investigate the influence of model maturity on Life Cycle Assessment (LCA) outcomes, the case study building described in Section 5.2 was modelled three separate times in Autodesk Revit, corresponding to three distinct Level of Development (LOD) stages: LOD 100, LOD 200, and LOD 300, as defined by the Level of Development (LOD) Specification [31].

As previously noted, the modelling process followed the Level of Development (LOD) Specification published by BIMForum (2025) [31]. This specification constitutes an organized compilation of interpretations of the American Institute of Architects' (AIA) original LOD definitions, providing detailed input and information requirements alongside graphical examples for a wide range of building element classes at each level of development. Rather than applying a generalized or uniform level of detail across the entire model, each building element was modelled in accordance with its specific definition within the specification; that is, for every element, the corresponding LOD 100, LOD 200, or LOD 300 requirement (for example, the specific criteria for an "LOD 300 exterior wall") was individually consulted and used as the modelling target, ensuring that the geometric and informational content of every element corresponded precisely to the requirements established for the relevant LOD stage.

Across all three models, the overall building geometry, site location, orientation, and structural system remained identical. The building is characterized by a load-bearing masonry structure with concrete floor slabs and a concrete foundation, and this fundamental structural configuration was preserved consistently across all three LOD models. The only variable that changed between models was the level of development applied to individual building elements, meaning the degree of geometric and material detail with which each element was represented, not the underlying structural design itself. This controlled approach was adopted deliberately. By holding the building's structural system and overall configuration constant, any differences observed in the resulting LCA outcomes can be attributed specifically to the progressive refinement of geometric and non-geometric information across the three LOD stages, rather than to unrelated differences in the building design.

The following subsections describe how each LOD stage was implemented in practice. For each stage, the geometric representation and the associated material information assigned to the building's key elements, namely the external and internal walls, floor slabs, foundation, staircase, and roof, are described in detail.

5.3.2. SUBSTRUCTURE (FOUNDATION & BELOW-GRADE)

As shown in Table 3, the substructure system comprises three elements: the foundation, the subgrade enclosure wall construction, and the basement slab-on-grade. Each element was modelled according to its individual LOD 100, LOD 200, and LOD 300 definitions, as detailed below.

5.3.2.1. GENERAL LOD 100 PRINCIPLE

According to the AIA Contract Document (G202) fundamental LOD 100 definition, a Model Element at this stage "may be graphically represented in the Model with a symbol or other generic representation but does not satisfy the requirements for LOD 200." Any associated information (e.g., cost per square foot, tonnage) may instead be derived from other Model Elements. BIMForum's expansion of this

definition clarifies that LOD 100 elements are not necessarily geometric representations; they may instead take the form of symbols indicating the existence of a component without conveying its shape, size, or precise location, or of generic space-reservation volumes [31]. Any information derived from an LOD 100 element must therefore be treated as approximate.

Consistent with this principle, the substructure at LOD 100 was represented using solid mass modelling rather than discrete, distinguishable building elements. Specifically, the case study building was divided into three solid masses at this stage: one representing the basement and foundation combined, one representing the volume from ground floor to first floor, and one representing the roof. This satisfies the LOD 100 requirement for the subgrade enclosure wall, which specifies a "solid mass model representing the overall subgrade volume, or schematic wall elements that are not distinguishable by type or material," while the foundation itself, per its own LOD 100 definition, is not graphically represented and instead falls under the same fundamental LOD 100 principle described above.

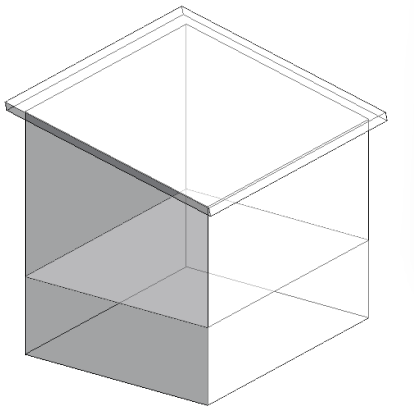


Figure 13 - LOD 100 mass model of the case study building in Revit

5.3.2.2. FOUNDATION

At LOD 200, the foundation requirement calls for inclusion of the element's envelope, defined as its approximate exterior surfaces. Accordingly, the foundation was modelled in Revit as a raft (mat) foundation with a thickness of 300 mm. At LOD 300, the foundation type was revised to a strip footing running along the load-bearing walls, increasing the thickness from 300 mm to 400 mm. This change reflects the LOD 300 requirement for an accurate, rather than approximate, representation of the foundation: at earlier design stages, the specific foundation type is often not yet known or finalised, whereas by LOD 300 sufficient design development has occurred to justify a more precise and realistic foundation solution.

Table 3 - BIMForum [31] LOD 100/200/300 definitions for substructure system

Number	Element	LOD 100	LOD 200	LOD 300
A1010	Standard Foundation	See the Fundamental LOD definition	Inclusions: Element envelope	Inclusions: Openings requiring formwork Surface slopes Area of Influence

A2010	Subgrade Enclosure Wall Construction	Solid mass model representing overall subgrade volume or schematic wall elements that are not distinguishable by type or material	Inclusions: Approximate thickness of the layer represented by a single element	Inclusions: Single model element with overall thickness and shape Openings requiring formwork at **nominal** dimensions
A4010	Standard Slabs-on-Grade	N/A	Inclusions: Generic slab with approximate thickness	Inclusions: Overall size, thickness, and geometry Openings requiring formwork Depressions Edge turn downs Surface slopes Area of influence

5.3.2.3. SUBGRADE ENCLOSURE WALL

At LOD 200, the subgrade enclosure wall requirement specifies a single, undifferentiated element; accordingly, it was modelled as a single-layer concrete wall with a width of 370 mm, a dimension taken from the case study building's AutoCAD drawings. Since the original drawings did not specify a material, concrete was assumed for this element. At LOD 300, the wall was developed into a layered construction consistent with the increased material specificity required at this stage, comprising a 10 mm damp-proofing finish layer, an 80 mm rigid insulation thermal/air layer, and a 280 mm concrete structural layer, as shown in Table 4. The overall wall width was kept consistent with the LOD 200 model to isolate the effect of layer composition from changes in overall dimension.

Table 4 - Layer composition of Subgrade Enclosure Wall at LOD 300

Function	Material	Thickness (mm)
Finish	Damp-proofing	10.0
Thermal/Air Layer	Rigid insulation	80.0
Structure	Concrete	280.0

5.3.2.4. BASEMENT SLAB

The basement slab was treated differently between LOD 200 and LOD 300 due to the change in foundation type described above. At LOD 200, the 300 mm mat foundation itself functions directly as the basement slab, since the raft foundation spans the entire basement footprint and the basement floor sits directly upon it. At LOD 300, however, the shift to a strip footing running along both the load-bearing external and internal walls meant that the foundation no longer provided a continuous slab surface; a separate basement slab therefore had to be introduced. This LOD 300 slab comprises a 10 mm slab

screed finish layer, an 80 mm rigid insulation layer, and a 100 mm concrete structural layer. For the purposes of result comparison, this slab is considered part of the foundation element rather than a separate component, since excluding it would render the LOD 200 and LOD 300 foundation values non-comparable (the LOD 200 mat foundation inherently includes the slab function, while the LOD 300 strip footing does not). The addition of insulation to both the subgrade enclosure wall and the basement slab at LOD 300 reflects the design of an insulated basement.

At LOD 200, the subgrade enclosure wall was represented as a single concrete element, consistent with BIMForum's [31] requirement for an approximate thickness represented by a single element. At LOD 300, while BIMForum's [31] minimum requirement is limited to defining the overall thickness, shape, and formwork openings, the wall assembly was expanded to include rigid insulation and damp-proofing layers, reflecting standard construction practice for below-grade enclosure walls, where moisture protection and thermal insulation are functionally necessary; this represents an appropriately detailed refinement consistent with the intent of LOD 300 to represent constructible, real-world assemblies.

Table 5 - Layer composition of Basement Slab at LOD 300

Function	Material	Thickness (mm)
Finish 1	Slab Screed	10.0
Thermal/Air Layer	Rigid insulation	80.0
Structure	Concrete	100.0

5.3.3. SHELL SUPERSTRUCTURE

The shell superstructure comprises four elements, classified according to the BIMForum system as B1010.20.40 (Floor Decks, Slabs, and Toppings – Concrete), B1020.10 (Roof Structural Frame), B1020.20 (Roof Decks, Slabs, and Sheathing), B3010 (Roofing), and B1080 (Stairs) [31]. Each element was modelled according to its individual LOD 100, LOD 200, and LOD 300 definitions, as detailed below.

5.3.3.1. FLOOR SLAB

At LOD 100, the floor slab requirement specifies only an approximate location for the element, without geometric or material definition. At LOD 200, the requirement expands to include the element's envelope, meaning its approximate exterior surfaces; accordingly, the floor slab was modelled as a single concrete layer with a thickness of 250 mm. At LOD 300, the requirement shifts toward greater geometric accuracy and material specificity: the overall slab thickness was kept the same, but the single concrete layer was subdivided into a 200 mm structural concrete layer and a 50 mm slab screed finish layer, reflecting the increased construction detail expected at this stage while preserving the total dimension established at LOD 200.

Table 6 - BIMForum [31] LOD 100/200/300 definitions for shell superstructure system

Number	Element	LOD 100	LOD 200	LOD 300

B1010.20.40	Floor Decks, Slabs, and Toppings (Concrete)	Inclusions: Abstraction of element indicating approximate location	Inclusions: Element envelope of individual members	Inclusions: Slopes and elevation changes (e.g., depressions) Drainage low points Openings requiring formwork Changes of material Edge locations Framing members
B1020.10	Roof Structural Frame	Inclusions: Abstraction of element indicating approximate location	Inclusions: Element envelope of individual members	Inclusions: Specific member shape; Spacing and end elevations; All planned openings;
B1020.20	Roof Decks, Slabs, and Sheathing	Inclusions Conceptual depth	Inclusions: Element envelope	Inclusions: Surface slopes Openings that require formwork or additional reinforcement Curbs and equipment pads
B3010	Roofing	Inclusions: Solid mass model representing overall building volume; or, schematic wall elements that are not distinguishable by type or material.	Inclusions: Element envelope at average thickness	Inclusions: Surface slopes Intended location of roof drains Openings that require additional reinforcement. Modules (if applicable)
B1080	Stairs	Inclusions: Approximate location	Inclusions: Reliable number and arrangement of landings and flights	Inclusions: Overall geometry of landings and flights Number of risers and treads Tread width Riser height Stringers Railing

5.3.3.2. ROOF

The BIMForum [31] specification classifies the roof into three distinct categories: the roof structural frame, roof decks and sheathing, and roofing, implying that these are typically represented as separate construction layers. For this thesis, this classification was simplified by evaluating a single Revit roof element against all three applicable categories at each LOD stage, rather than modelling them as three separate objects, since Revit's compound layer system allows a single element to represent multiple functional layers within one assembly. This simplification was adopted for modelling efficiency and does not affect the validity of the LOD comparison, since the same approach was applied consistently across all three LOD stages.

At LOD 100, the roof was represented using the same solid mass modelling approach described in Section 5.3.2, consistent with the general LOD 100 principle of generic, non-differentiated volumetric representation. At LOD 200 and LOD 300, the roof was developed into a fully layered construction reflecting an insulated timber rafter build-up, comprising, from exterior to interior: a 20 mm roofing tile finish layer, a 24 mm wood fibreboard finish layer, a 160 mm rock wool thermal/air layer, an 80 mm timber joist/rafter structural layer, and a 12.5 mm gypsum wallboard internal finish layer, as shown in Table 7.

Table 7 - Layer composition of Roof at LOD 300

Function	Material	Thickness (mm)
Finish	Roofing, Tile	20.0
Finish	Wood Fiberboard	24.0
Thermal/Air Layer	Rock Wool	160.0
Structure	Structure, Timber Joist/Rafter Layer	80.0
Finish 2	Gypsum Wall Board	12.5

5.3.3.3. STAIRS

At LOD 100, the stairs were not included in the model, consistent with the general LOD 100 principle whereby elements not yet required for approximate representation may be omitted entirely. At LOD 200, the stairs were modelled with a basic level of geometric detail, represented simply by risers and treads. At LOD 300, the same geometry was retained, with railings and stringers added to increase the level of visual and structural detail; the stair geometry itself was not further refined beyond this addition. This represents a minor simplification relative to the strict LOD 300 definition, adopted for practicality, since the stairs were not considered a primary element of interest for the LCA comparison in this thesis.

Each element was modelled according to its individual LOD 100, LOD 200, and LOD 300 definitions, as detailed below.

5.3.4. SHELL EXTERIOR VERTICAL ENCLOSURES

The shell exterior vertical enclosure system comprises elements classified according to the BIMForum system as B2010.20.30 (Exterior Wall Construction – Masonry), B2010.30 (Exterior Wall Interior Skin), B2010.10 (Exterior Wall Veneer), B2020 (Exterior Operating Windows), and B2050 (Exterior Doors and Grilles, limited in this case to exterior doors only, as the case study building does not include grilles) [31].

Table 8 - BIMForum [31] LOD 100/200/300 definitions for shell exterior vertical enclosures

Number	Element	LOD 100	LOD 200	LOD 300
B2010.20.30	Exterior Wall Construction (Masonry)	Inclusions: Solid mass model representing overall building volume; or, schematic wall elements that are not distinguishable by type or material.	Inclusions: Approximate thickness of layer represented by a single element.	Inclusions: Single model element with overall thickness and shape Planned openings at **nominal** dimensions
B2010.30	Exterior Wall Interior Skin	N/A	Inclusions: Approximate thickness of layer	Inclusions: Single model element separated by type of material with overall thickness and shape Openings that require additional reinforcement, at nominal dimensions
B2010.10	Exterior Wall Veneer	N/A	Inclusions: Approximate overall wall thickness represented by a single assembly.	Inclusions: Model elements separated by type of material Openings that require additional reinforcement Window and door openings at nominal dimensions
B2020	Exterior Operating Windows	N/A	Generic window object	Inclusions: Specific type and size Direction of opening

B2050	Exterior Doors and Grilles — for your house, mainly the exterior doors part	N/A	Inclusions: Generic object	Inclusions: Specific door panels and frames (if applicable) Operation If clearances are to be modelled, indicate in a note Panic bars if applicable

5.3.4.1. EXTERIOR WALL

At LOD 100, the exterior wall was represented using the same solid mass modelling approach described in the preceding subsections, consistent with the general LOD 100 principle of generic, non-differentiated volumetric representation of the overall building envelope. At LOD 200 and LOD 300, in accordance with the BIMForum [31] definitions for exterior wall construction, exterior wall interior skin, and exterior wall veneer, the wall was developed into a fully layered assembly, with the three BIMForum-classified components represented as distinct layers within a single Revit wall element rather than as physically separate wall objects, consistent with the compound layer approach adopted for the roof in Section 5.3.3. The overall wall thickness was different from LOD 200 moving from approximate thicktness the exact thickness of the layers. The structural layer of the common brick was kept the same with thickness of 175 mm. The finish layers were kept to 15 mm for both internal and external in LOD 200 while in LOD 300 we see 20 and 15 mm. And the biggest difference is the insulation layers which goes from 100 to 160 from LOD 200 to 300

Table - 9 Layer composition of Exterior Wall at LOD 200 and 300

Function	Material	LOD 200 (Thickness (mm)	LOD 300 (Thickness (mm)
Finish	Render, Beige, Smooth	15	20.0
Thermal/Air Layer	EIFS, Exterior Insulation	100	160.0
Structure	Brick, Common	175	175.0
Finish	Plaster	15	15.0

5.3.4.2. WINDOWS AND DOORS

At LOD 100, windows and doors were not represented in the model, consistent with the general LOD 100 principle whereby elements not required for approximate volumetric representation may be omitted. At LOD 200 and LOD 300, windows and doors were modelled in the same manner, with no further detail differentiation between the two stages. This decision reflects a deliberate simplification adopted for practical reasons: Revit provides well-defined, manufacturer-style families for windows and doors, with standardised geometry and properties already built into the software. Since architects and designers typically select from such predefined families in practice, rather than custom-modelling openings from first principles, it was assumed that this same workflow adequately represents both LOD 200 and LOD 300 requirements for these elements. Windows were further modelled to match the

dimensions and placement shown in the case study building's AutoCAD drawings, ensuring geometric consistency with the original design regardless of the LOD stage being represented.

5.3.5. INTERIOR CONSTRUCTION

The interior construction system comprises elements classified according to the BIMForum system as C1010.10.10 (Interior Wall – Masonry) and C1010.10.20 (Interior Wall – Cold-Form Metal Framing). Based on the wall widths identified in the case study building's drawings, three distinct interior wall types were identified and modelled: a load-bearing masonry wall and a non-load-bearing masonry wall, both falling under C1010.10.10 and distinguished from one another by thickness and structural role, and a partition wall constructed with metal stud framing, falling under C1010.10.20. Each wall type was modelled according to its corresponding LOD 100, LOD 200, and LOD 300 definitions, as detailed below.

Table 10 - BIMForum [31] LOD 100/200/300 definitions for interior construction

Number	Element	LOD 100	LOD 200	LOD 300
C1010.10.10	Interior Wall (Masonry)	N/A	Inclusions: Approximate overall wall thickness represented by a single element. Full vs partial height not differentiated	Inclusions: Composite model element at overall thickness Measurable individual layers (e.g. GWB, studs) Locations, heights (full vs partial height) Openings requiring additional framing at **nominal dimensions**
C1010.10.20	Interior Wall (Cold-Form Metal Framing)	N/A	Inclusions: Approximate overall wall thickness represented by a single element Full vs partial height not differentiated	Inclusions: Composite model element at overall thickness Measurable individual layers (e.g. GWB, studs) Locations, heights (full vs partial height), Openings requiring additional framing at **nominal dimensions**

At LOD 100, interior walls were not modelled at all; consistent with the solid mass modelling approach adopted for other elements at this stage, the mass model at LOD 100 represents only the overall building volume, without any indication of internal spatial subdivision. This is consistent with the general LOD 100 principle whereby elements not required for approximate volumetric representation may be omitted entirely.

At LOD 200, each of the three wall types was represented as a single, homogeneous structural layer, without the finish layers included at LOD 300; in Revit, this was implemented by defining only the

structural component of each wall assembly. The overall thickness of each wall type was set to match its structural LOD 300 thickness from the outset, specifically 210 mm for the load-bearing masonry wall, 150 mm for the non-load-bearing masonry wall, and 95 mm for the metal stud partition wall, so that the transition to LOD 300 involved only a change in layer composition, not a change in overall dimension.

At LOD 300, each wall type was developed into a fully layered assembly, consistent with the increased material specificity expected at this stage. The load-bearing masonry wall was modelled with a 15 mm plaster finish layer on each side and a 210 mm common brick structural core, for a total thickness of 240 mm, as shown in Table 11. The non-load-bearing masonry wall followed the same layer configuration, with a 15 mm plaster finish on each side and a 150 mm common brick structural core, for a total thickness of 180 mm, as shown in Table 12. The metal stud partition wall was modelled with a 12.5 mm gypsum wallboard finish layer on each side and a 95 mm metal stud structural layer, for a total thickness of 120 mm, as shown in Table 13. In all three cases, the overall wall thickness established at LOD 200 was preserved unchanged at LOD 300, with the only difference between the two stages being the subdivision of the single structural layer into distinct finish and structural layers.

Table 11 - Layer composition of load-bearing masonry wall at LOD 200 and 300

Function	Material	LOD 200 Thickness (mm)	LOD 300 Thickness (mm)
Finish	Plaster	-	15.0
Structure	Brick, Common	210	210.0
Finish	Plaster	-	15.0

Table 12 - Layer composition of non-load-bearing masonry wall at LOD 200 and 300

Function	Material	LOD 200 Thickness (mm)	LOD 300 Thickness (mm)
Finish	Plaster	-	15.0
Structure	Brick, Common	150	150.0
Finish	Plaster	-	15.0

Table 13 - Layer composition of metal stud partition wall at LOD 200 and 300

Function	Material	LOD 200 Thickness (mm)	LOD 300 Thickness (mm)
Finish	Gypsum Wallboard	-	12.5
Structure	Metal Stud layer	95	95.0
Finish	Gypsum Wallboard	-	12.5

5.3.6. INTERIOR FINISHING

The interior finishing system comprises elements classified according to the BIMForum system as C2010 (Wall Finishes), C2020 (Interior Fabrications), C2030 (Flooring), C2040 (Stair Finishes), and C2050 (Ceiling Finishes). Unlike the structural and enclosure elements described in the preceding subsections, interior finishes were not modelled as part of the compound layer assemblies of walls, floors, or roofs; rather, they are treated by the BIMForum specification as a distinct category, evaluated according to its own LOD progression, which is described below.

Table 14 - BIMForum [31] LOD 100/200/300 definitions for interior finishing

		LOD 100	LOD 200	LOD 300
C2030.45	Wood Flooring Plaster / Gypsum ceiling finish Tile Flooring	N/A	Inclusions: Area defined	Inclusions: Thickness if greater than ¼" (6 mm) or per user-defined keynotes

At LOD 100, interior finishes are not represented at all, consistent with the general LOD 100 principle whereby non-essential elements are omitted from the model in favour of generic volumetric representation. At LOD 200, the requirement shifts to inclusion of the finish at the level of area only, meaning that finishes were accounted for as a surface quantity, for example the area of flooring, wall surface, roof underside, or stair surface, without a defined thickness or material composition at this stage. At LOD 300, the BIMForum specification introduces a specific materiality threshold: a finish is only required to be explicitly modelled if its thickness exceeds 6 mm. In this thesis, all interior finish layers applied across the case study building exceeded this 6 mm threshold and were therefore included at LOD 300 with defined material and thickness values, consistent with the finish layers already described for the interior walls, exterior wall, roof, and slab assemblies in the preceding subsections (Sections 5.3.2 to 5.3.5).

5.3.7. ELEMENTS NOT INCLUDED

The Revit models developed for this study do not represent every building element or system present in the case study building; certain categories were deliberately excluded from the scope of modelling. Specifically, all building services, including plumbing systems and Heating, Ventilation, and Air Conditioning (HVAC) appliances, were excluded from the model, as were electrical systems and appliances, including lighting fixtures and associated wiring infrastructure.

This exclusion was adopted for two main reasons. First, incorporating detailed services and electrical systems across all three LOD stages would have substantially increased the size and complexity of the Revit models, resulting in a heavier, more computationally demanding model without contributing proportionate insight into the specific research question addressed in this thesis, namely how LOD progression in architectural and structural elements affects embodied carbon results. Second, this exclusion is consistent with common practice in BIM-based LCA research, where the majority of studies similarly limit their scope to structural and architectural elements and exclude MEP (Mechanical, Electrical, and Plumbing) systems, given the added complexity and separate modelling conventions these systems typically require.

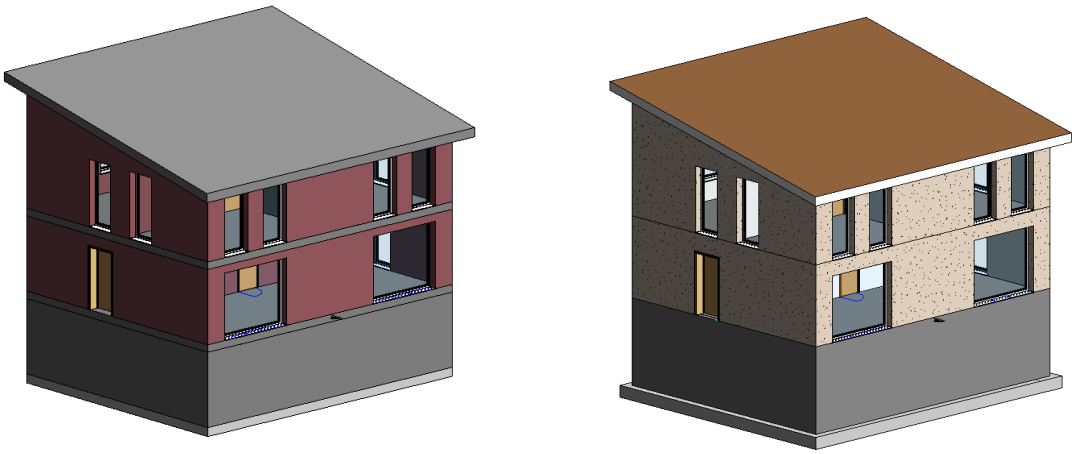


Figure 14 - LOD 200 (left) and LOD 300 (right) models of the case study building in Revit

5.4. LCA WORKFLOW IN ONE CLICK LCA

5.4.1. SOFTWARE SELECTION AND JUSTIFICATION

Previous studies comparing LCA results across different Levels of Development have predominantly relied on other LCA tools and databases, such as SimaPro, GaBi, or Tally, with One Click LCA appearing comparatively rarely in this specific area of research. This is likely attributable to the fact that One Click LCA, while founded in 2001, has only in recent years grown into one of the most prominent and widely adopted LCA platforms in the construction industry; it is now used across more than 170 countries and by major international firms such as Skanska, WSP, Foster+Partners, and Saint-Gobain, and has been recognized in industry publications such as the Verdantix 2025 Buyer's Guide for LCA software as a leading platform for AI-driven LCA and EPD automation. Its growing market position, expanding global database of verified environmental datasets, and increasing integration with widely used BIM software make it an increasingly relevant tool for LCA research. Yet, its use remains largely unexplored in academic studies specifically comparing LOD-based LCA outcomes. This thesis therefore contributes a novel perspective to the field by applying One Click LCA. This platform has recently emerged as an industry-leading solution but remains underrepresented in this specific strand of academic literature on the LOD comparison problem [73].

One Click LCA offers access to one of the largest verified LCA databases available, comprising more than 250,000 verified environmental datasets, and incorporates AI-assisted automation features to streamline carbon assessment workflows. The platform supports compliance with more than 80 international certification and reporting schemes, including LEED, BREEAM, and EN 15978. It integrates with more than 20 BIM software applications, including Autodesk Revit, Tekla Structures, and Bentley iTwin. It further provides early-stage carbon optimisation capabilities through its Carbon Designer 3D tool, and is designed to accommodate a broad range of users, from individual practitioners to large multinational organizations [73].

For this thesis specifically, One Click LCA was selected primarily due to its availability through the university's software license and its accessible, user-friendly interface, which made it a practical choice for conducting repeated LCA runs across three separate LOD-stage models within the scope of a master's thesis.

The One Click LCA platform offers two primary means of conducting an assessment: a plugin integrated directly within Autodesk Revit, allowing the LCA to be performed within the modelling environment, or

exporting material quantity data for assessment within the One Click LCA cloud platform. For this research, the cloud version was selected over the Revit plugin, primarily because the cloud platform provides access to a broader range of graphical outputs. This same workflow, exporting material quantities from Revit and conducting the assessment within the One Click LCA cloud platform, was applied consistently across all three LOD-stage models, ensuring that any differences in results stem from the underlying LOD-based material data rather than from inconsistencies in the assessment procedure itself [40].

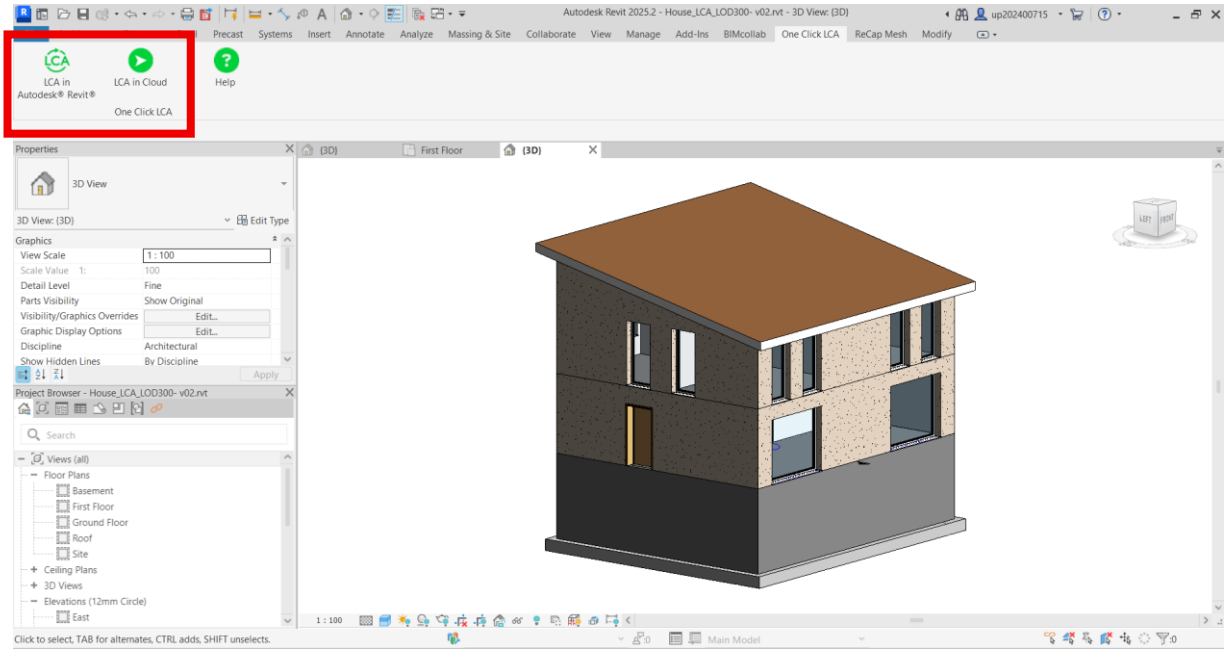


Figure 15 - One Click LCA plugin interface within Autodesk Revit

Before conducting the LCA, the initial project setup parameters were defined within One Click LCA, establishing the fundamental characteristics of the case study building against which the material and assembly data from each LOD-stage model would be assessed. Table 15 summarises the key project setup parameters used consistently across all three LOD-stage assessments, ensuring that the building's basic classification, location, and physical characteristics remained constant throughout the comparison, in line with the controlled-variable approach described in Section 5.3.1.

Regarding the frame type parameter, the case study building was classified as "Other/mixed frame," since One Click LCA's predefined dropdown options did not include a specific category corresponding to the building's actual load-bearing masonry structure; "Other/mixed frame" was therefore selected as the closest available generic classification. Regarding the project address, Giessen, Germany was entered primarily for project identification and documentation purposes. While location data can also influence certain location-dependent defaults within One Click LCA, such as transportation distance assumptions for materials, this parameter was not material to the present study, since the system boundary was restricted to the A1-A3 production stages only, as detailed in Section 5.4.5; transportation to the construction site (module A4) falls outside this boundary and was therefore not affected by the specified project location.

Table 15 - One Click LCA project setup parameters for the case study building

Type	One-dwelling buildings

Adress	Giessen, Germany
Country	Germany
Gross Floor Area	274 m2
Number of above-ground floors	2
Frame type	Other/mixed frame

5.4.2. CALCULATION TOOL AND STANDARD SELECTION

The specific calculation tools available within One Click LCA depend on the type of license held by the user. For this thesis, access to One Click LCA was provided through the institutional license held by Technische Hochschule Mittelhessen University of Applied Sciences (THM). This license provides access to a limited selection of calculation tools rather than the platform's full range of options; specifically, only the Level(s) life-cycle assessment tools are available under this license. As a result, the DGNB-specific calculation tool, which would have applied DGNB's own built-in calculation engine, was not accessible, and the study was consequently limited to conducting the LCA using the Level(s) framework. To maintain methodological alignment with DGNB standards despite this limitation, DGNB's parameter recommendations and guidelines, including service life values, transportation scenarios, and material manufacturing localisation settings, were applied manually within the Level(s) calculation tool, as detailed in Section 5.4.4, rather than relying on DGNB's dedicated calculation engine.

Within the Level(s) framework, One Click LCA offers four distinct calculation tools, which differ according to their scope of environmental impact coverage and their compliance with either the older EN 15804 +A1 standard or the more recent +A2 standard. Table 16 summarises the scope and standard compliance of each of the four available tools.

Table 16 - Overview of One Click LCA calculation tools available under the Levels framework

Tool Name	Focus Scope	Standard Compliance	Best Used For
1. Level(s) life-cycle carbon (+A1/+A2)	Greenhouse Gas (GHG) / Carbon Only	Both +A1 & +A2 data accepted	Fast carbon-footprint screenings and basic Level(s) Macro-Objective 1 compliance.
2. Level(s) LCA (+A1)	Full LCA (All environmental impacts)	Older EN 15804 +A1 standard	Projects using legacy +A1 material data or benchmarking against older building models.
3. Level(s) LCA (+A2) - additional	Extension impacts (toxicities, land use, etc.)	Modern EN 15804 +A2 standard	Voluntary, deeper environmental reporting alongside the core +A2 impacts.
4. Level(s) LCA (+A2)	Full LCA (All environmental impacts)	Modern EN 15804 +A2 standard	Complete, compliant building LCAs according to current EU frameworks.

EN 15804 constitutes the core European standard defining how Environmental Product Declarations (EPDs) for construction products are developed and structured. The standard has undergone a significant update, from the original +A1 amendment to the more recent +A2 amendment, which mandates a more comprehensive scope of life-cycle assessment, including the consideration of biogenic carbon and

resource use indicators not required under +A1. Critically, data generated under the two amendments is fundamentally incompatible, meaning that EPDs developed under +A1 cannot be directly compared with, or combined with, EPDs developed under +A2 within the same building assessment [88], [89].

Several key differences distinguish between the two standards. In terms of indicators and metrics, +A2 introduces 19 core environmental indicators, a substantial expansion relative to the seven core indicators defined under +A1. Regarding Global Warming Potential (GWP), +A1 reports a single aggregated GWP value, whereas +A2 disaggregates this metric into fossil, biogenic, and land-use change components, a separation intended to prevent hidden carbon offsets and reduce the risk of greenwashing in reported results. In terms of system boundaries, +A2 requires more detailed and standardized tracking of a product's end-of-life stage (modules C1-C4) and of benefits and loads beyond the system boundary (module D). Finally, in terms of data comparability, because the underlying calculation methods and characterisation factors differ between the two amendments, EPDs created under +A1 cannot be directly compared or mixed with EPDs created under +A2 within the same assessment [88], [89].

The +A2 amendment was introduced to align construction-sector EPDs more closely with broader European circular economy and sustainability objectives, and all newly issued EPDs are now expected to comply with this updated standard. Consequently, when conducting building-level LCAs or selecting construction materials, practitioners must ensure that all EPD datasets used within a given assessment adhere to the same standard version, to avoid introducing incompatible or non-comparable data into the results [88], [89].

Considering the four available Level(s) tools summarized in Table 16, this thesis employed the Level(s) LCA (+A2) tool, on account of two primary considerations. First, this tool complies with the most recent and currently mandated EN 15804 +A2 standard, ensuring that the results generated align with current European regulatory and industry expectations, rather than relying on the increasingly obsolete +A1 standard used by Tool 2. Second, the +A2 tool calculates a full, multi-criteria environmental footprint, encompassing impact categories such as acidification and eutrophication potential, in addition to global warming potential; this broader scope is required for alignment with DGNB assessment criteria, whereas Tool 1 is restricted to carbon-only reporting and is therefore insufficient for this purpose [88], [89]. By adopting the modern EN 15804 +A2 framework from the outset, this tool further ensures that the material inventory compiled during the material mapping process (Section 5.4.6) is structured in a manner consistent with current and future data requirements, rather than requiring later reconciliation with an outdated standard."

5.4.3. LOD-TO-DESIGN-STAGE MAPPING

In addition to defining the general project setup parameters, One Click LCA requires the assessor to specify the project's development stage at the time of assessment, drawing on standardised design stage frameworks published by RIBA (Royal Institute of British Architects) and AIA (American Institute of Architects). Since this thesis compares LCA outcomes across three distinct Levels of Development, each of the three LOD-stage models needed to be assigned to its corresponding project development stage within the software, ensuring that the platform's stage-dependent defaults and assumptions were configured appropriately for each model.

The LOD 100 model was matched to the Preparation & Brief/Pre-Design stage, reflecting its early, conceptual level of geometric and material definition. The LOD 200 model was matched to the Concept Design/Schematic Design stage, corresponding to its intermediate level of development, where element envelopes are approximated but not yet finalised. The LOD 300 model was matched to the Spatial Coordination/Design Development stage, reflecting its more advanced and coordinated level of geometric and material accuracy. This mapping ensured that each LOD-stage assessment was evaluated within a project development context appropriate to its actual level of design maturity, maintaining

consistency between the modelling assumptions applied in Section 5.3 and the assessment configuration applied within One Click LCA [67]. It should be noted that it is not entirely certain whether this design stage setting actively influences One Click LCA's underlying calculation defaults or assumptions, or whether it serves primarily a documentation and reporting function within the platform; regardless, the mapping was applied consistently across all three models to maintain methodological transparency and consistency .

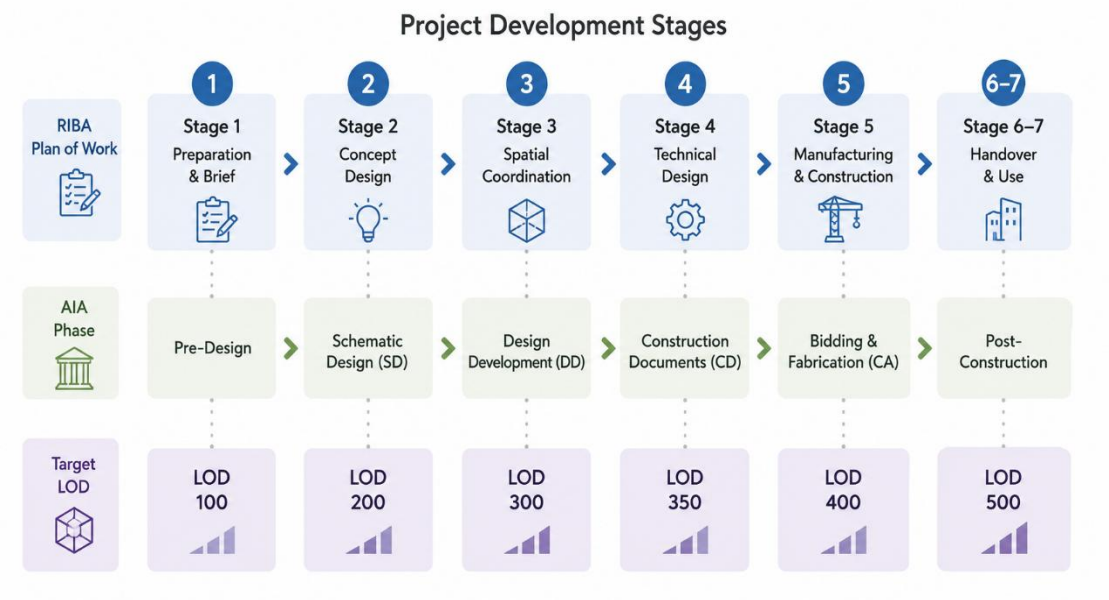


Figure 16 - Alignment of RIBA and AIA project stages with BIMForum LOD levels (AI-generated using ChatGPT)

5.4.4. LCA PARAMETERS AND ASSUMPTIONS

In addition to the general project setup and calculation tool selection described above, One Click LCA requires the assessor to define a series of calculation parameters that govern key assumptions underlying the LCA results. To maintain methodological consistency with DGNB's assessment guidelines, despite the DGNB calculation tool itself not being accessible under the available license (see Section 5.4.2), the parameters described below were configured manually in line with DGNB's recommended values [90].

Regarding the **service life** of individual materials, One Click LCA offers a choice between product-specific service life values and generic technical service life defaults, the latter representing default estimates of how long a given material type typically remains in acceptable condition. DGNB guidelines recommend that service life assumptions follow product-specific data as closely as possible, particularly given their influence on module B4 replacement calculations; this recommendation was followed in the present study wherever product-specific service life data was available [90].

Regarding **transportation scenarios for materials**, One Click LCA proposes typical default transportation distances based on material type and project location. The most geographically appropriate default transportation scenario, corresponding to the case study building's location, was selected for this parameter, although, as noted in Section 5.4.1, this parameter did not ultimately influence the reported results given the study's A1-A3 system boundary [73].

Regarding **material manufacturing localisation**, One Click LCA allows the assessor to adjust material manufacturing process emissions according to the grid electricity mix and energy efficiency profile of

the project's location. The Local Compensation Model v2.1, the current recommended version, was applied for the localisation method. For the localisation target, the DGNB-DE-Production-2023 - Utilization - 1 kWh national grid electricity mix - QNG profile was selected, as this profile aligns the calculation with DGNB and QNG (Qualitätssiegel Nachhaltiges Gebäude) requirements specific to the German context, ensuring methodological consistency and comparability of results within this national regulatory framework. This selection also ensures that electricity-related assumptions in the material manufacturing stage reflect the project's actual national setting rather than a generic, non-location-specific dataset.

Regarding the overall **building service life**, the calculation period was set to 50 years, in accordance with the reference period defined by the DGNB International system (2020) for new buildings; this reference period applies to standard building typologies and excludes production and logistics buildings, for which DGNB specifies a shorter 20-year reference period.

5.4.5. SYSTEM BOUNDARIES AND SCOPE

For an early-stage design assessment such as the one conducted in this thesis, a simplified embodied-carbon LCA focused on the production stage (modules A1-A3) is generally considered the most appropriate approach. At LOD 100 and LOD 200, the available geometry and material specifications remain too incomplete to support a reliable whole-life assessment; incorporating operational carbon at these earlier stages would therefore risk making the resulting outcomes more assumption-driven than genuinely decision-useful. Operational carbon estimates depend on a range of inputs, including building form, building systems, envelope performance, occupancy patterns, and energy model assumptions, all of which are still subject to substantial change at LOD 100 and LOD 200. As a result, operational carbon results calculated at these early stages can be highly unstable, potentially distracting from the embodied-carbon design decisions that can already be meaningfully influenced at this point in the design process. Early-stage embodied-carbon LCA is nonetheless valuable, as it allows low-embodied-carbon design alternatives to be identified early; however, final design decisions must ultimately balance embodied carbon savings against operational performance, a consideration that falls outside the scope of this thesis.

In light of these considerations, the system boundary adopted for this thesis is restricted to the embodied impact associated with the production stage, comprising modules A1 (raw material supply), A2 (transport to the manufacturing site), and A3 (manufacturing). This boundary explicitly excludes transportation to the construction site (module A4), operational energy use (module B6), operational water use (module B7), construction site operations (module A5), and maintenance (module B2), consistent with the study's focus on isolating the effect of LOD progression on embodied carbon results specifically, rather than on the building's total life-cycle environmental performance.

5.4.6. BUILDING MATERIAL MAPPING

Building material mapping is a critical step in the BIM-based LCA workflow, as it links the building elements defined in the Revit models to corresponding materials within the One Click LCA database that carry an associated Environmental Product Declaration (EPD). This linkage is what allows the material quantities extracted from the Revit models to be translated into environmental impact values, enabling the life cycle assessment to be conducted. Correct mapping between the Revit material data source and the LCA database is an important factor in reducing the time required to complete an assessment, since a mismatch commonly exists between the material naming conventions used in Revit and those used in underlying LCI databases such as Ecoinvent. The units of measurement defined for a given material often differ between the two systems. One Click LCA attempts to address this challenge by automatically

matching materials imported from the BIM model to environmental data based on their textual description, and the platform also offers an AI-assisted automated mapping feature intended to streamline this process further.

5.4.6.1. MAPPING METHODOLOGY AND DATABASE SELECTION

To comply with German regulatory requirements, the Ökobaudat database was selected as the source of environmental data for material mapping in this thesis. Within Ökobaudat, it was ensured that all materials selected were compliant with the EN 15804 +A2 standard, the newer of the two amendments to the EN 15804 standard, rather than the older +A1 version, consistent with the calculation tool selection described in Section 5.4.2 [91]. Additionally, Generic EPDs were selected in preference to manufacturer-specific EPDs throughout the mapping process. This choice reflects the early and comparative nature of this thesis's design stages, in which manufacturer-specific product data would not typically be available or appropriate, and ensures that the same generic, non-brand-specific environmental profiles were applied consistently across all three LOD-stage models.

5.4.6.2. AUTOMATIC VS MANUAL MAPPING PROCESS

Despite One Click LCA's automatic mapping capability, materials imported from the Revit models were not successfully identified automatically in the majority of cases. In addition to this identification failure, mismatches between the units of measurement used in the Revit material data and those required by the Ökobaudat database further complicated the automatic mapping process. As a result, it was found to be more reliable to map materials manually, one by one, rather than relying on the platform's automated matching feature. This manual approach, while more accurate, was considerably more time-consuming than an automated workflow would have been.

The need for manual mapping was particularly pronounced at LOD 200, where building elements were often represented generically or with limited material definition, as described in Section 5.3. Since these generic or undefined materials could not be automatically matched to a specific environmental profile, each required manual assignment of a suitable substitute from the Ökobaudat database, based on the closest reasonable match to the element's intended material composition. LOD 100 is not included in this discussion, since, as described in Section 5.3.2, the LOD 100 model consists solely of a generic solid mass representation without any assigned material information; consequently, no automatic or manual material mapping was applicable or expected at this stage. The LCA at LOD 100 was instead conducted using an entirely separate, assumption-based quantity takeoff approach, detailed in Section 5.4.6.5.

5.4.6.3. ELEMENT-SPECIFIC MAPPING ADJUSTMENTS

Beyond the general mapping challenges described above, several specific building elements required additional manual adjustment to ensure that the imported material data accurately reflected the intended level of development. One notable issue arose with door and window elements, as mentioned in Section 5.3.4. Doors and windows were modelled using predefined Revit families, which are inherently detailed to a level of geometric definition exceeding both LOD 200 and LOD 300. When these families were imported into One Click LCA, doors were automatically subdivided into four separate sub-components: door-architrave, door-frame/mullion, door-handle, and door-panel. Since this level of componentry exceeds what is required at LOD 200, the architrave, frame/mullion, and handle sub-components were deleted from the assessment, retaining only the door panel to align the assessed level of detail with the corresponding LOD requirement.

A comparable issue arose with window elements, which were similarly subdivided upon import into window glass and window frame sub-components. In this case, the window frame was excluded from the assessment at LOD 200. For LOD 300, the door-frame and window frame were added, since the frame's level of detail was considered consistent with the intended LOD representation at the LOD 300 stage.

A further adjustment was required for the quantity of metal studs used in the non-load-bearing partition walls. Since the project remained at an early design stage and no manufacturer-specific stud system had been specified, a generic galvanised steel stud dataset was selected from the Ökobaudat database. At LOD 200, wall geometry and stud spacing are rough/assumed (e.g., a wider generic 600 mm spacing, reflecting less design certainty). At LOD 300, the same generic Ökobaudat product (6.5 kg/m) is used, but spacing has been refined to the actual specified 500 mm centre, reflecting more precise design intent.

The wall run under consideration had a total length of 17.3125 m and a height of 2.27 m. Assuming a stud spacing of 500 mm centre-to-centre, the number of studs required was calculated as the total wall length divided by the stud spacing, with one additional end stud added to account for the wall's terminating edge:

$$n_{studs} = \frac{L}{s} + 1 \tag{1.1}$$

The total stud mass was then calculated by multiplying the number of studs by the wall height and the unit mass of the selected reference product:

$$m_{studs} = n_{studs} \times H \times m_{unit} \tag{1.2}$$

Using the same generic Ökobaudat reference product (6.5 kg/m) at both stages and only varying the stud spacing to reflect the design refinement between LOD 200 (600 mm, less certain) and LOD 300 (500 mm, specified), the results are shown in Table 17.

Table 17 - Metal Studs calculation

Parameter	**LOD 200**	**LOD 300**
Stud spacing	600 mm	500 mm
Unit mass	6.5 kg/m	6.5 kg/m
Number of studs	30	36
Total stud mass	442.6 kg	531.2 kg

At LOD 200 and 300, the roof structure was modelled in Revit as an "Insulated Timber Rafter Construction," with the structural layer assigned as a Timber Joist/Rafter layer of 80 mm thickness, mapped to "Solid construction timber (15% moisture / 13% H2O content)," with a density of 529 kg/m³, sourced from a generic EPD compliant with EN 15804+A2 (reference year 2023). As with the metal stud partitions, this layer is not a continuous solid timber slab in reality; rafters are discrete, load-bearing

structural members repeated at regular intervals across the roof area, with the space between adjacent rafters left as a void or filled with insulation material, rather than solid timber. Taking Revit's reported layer quantity at face value, as though the entire 80 mm layer were solid timber across the full roof area, would therefore substantially overestimate the actual timber volume and the corresponding embodied GWP contribution of this element, in the same way this issue was identified and corrected for the metal stud partition walls.

To correct for this, the actual timber volume was recalculated based on standard rafter dimensions and spacing typical of residential timber-frame roof construction, assuming a rafter width of 47 mm and a centre-to-centre spacing of 600 mm. This yields a timber coverage ratio of 7.83% of the total roof area (rafter width divided by spacing), applied to the 114 m^2 roof area and the 80 mm layer thickness, resulting in a corrected timber volume of approximately 0.71 m^3, equivalent to 377.92 kg at the specified density, rather than the 9.12 m^3 (approximately 4,824 kg) that would result from treating the layer as fully solid across the entire roof area.

As with the metal stud correction, the rafter width and spacing values used here were not derived from project-specific structural drawings, since none were available for this hypothetical case study, but were instead assumed based on standard values commonly applied in residential timber-frame roof construction.

5.4.6.4. BILL OF MATERIALS (LOD 200 AND LOD 300)

Following the mapping and quantity adjustments described above, a complete Bill of Materials was compiled for each LOD-stage model, listing every material assigned to each building element category, together with its associated quantity, unit of measurement, and, where applicable, its layer thickness. Table 18 presents the Bill of Materials for the LOD 200 model, organised by building part and element class.

Table 18 - Bill of Materials LOD 200

BUILDING PART	CLASS	MATERIAL	QUANTITY	QTY_TYPE	THICKNESS_MM
Foundation and Sub-surface	FOUNDATION	Ready-mix concrete C25/30, C25/30, 2300 kg/m3, EN15804+A2, ref. year 2023	27.41	m3	
External Walls and Façade	EXTERNAL WALL	Ready-mix concrete C25/30, C25/30, 2300 kg/m3, EN15804+A2, ref. year 2023	92.4	m2	370
	EXTERNAL WALL	Sand-lime brick, 2000 kg/m3, EN15804+A2, ref. year 2023	59.159	M3	
Internal and non-load-bearing walls	INTERNAL WALL	Sand-lime brick, 2000 kg/m3, EN15804+A2, ref. year 2023	25.45	m3	
	INTERNAL WALL	Galvanized steel stud, 500 mm centre, 6.5 kg/m (One Click LCA)	516.4	kg	

Stairs	STAIR	Ready-mix concrete C25/30, C25/30, 2300 kg/m3, EN15804+A2, ref. year 2023	0.45	m3	
Floor and Horizontal Elements	SLAB	Ready-mix concrete C25/30, C25/30, 2300 kg/m3, EN15804+A2, ref. year 2023	173.82	m2	250
	ROOF	Solid construction timber (15% moisture / 13% H2O content), 529 kg/m3, 15% moisture content, EN15804+A2, ref. year 2023	34.22	m3	
Doors and Windows	WINDOW	Insulated glazing, triple pane, 30 kg/m2, EN15804+A2, ref. year 2023	40.34	m2	
	DOOR	Wooden doors, calculated average for Germany, 1.23x2.18 m, 36 kg/m2, 96 kg/unit (One Click LCA)	21.81	m2	

Table 19 presents the corresponding Bill of Materials for the LOD 300 model. Compared to the LOD 200 bill of materials, the LOD 300 table reflects the layered construction approach adopted at this stage, as described in Section 5.3, with individual finish, insulation, and structural layers listed separately for each building element rather than as a single homogeneous material entry.

Table 19 - Bill of Materials LOD 300

BUILDING PART	CLASS	MATERIAL	QUANTITY	QTY_TYPE	THICKNESS_MM
Foundation and Sub-surface	FOUNDATION	Ready-mix concrete C25/30, C25/30, 2300 kg/m3, EN15804+A2, ref. year 2023	18.18	m3	
	FOUNDATION	Ready-mix concrete C25/30, C25/30, 2300 kg/m3, EN15804+A2, ref. year 2023	7.435	m3	
External Walls and Façade	EXTERNAL WALL	Damp insulation PE, 0.2 kg/m2, EN15804+A2, ref. year 2023	108.66	m2	
	EXTERNAL WALL	Gypsum interior plaster, 900 kg/m3, EN15804+A2, ref. year 2023	2.537	m3	

	EXTERNAL WALL	Mineral wool (facade insulation), 46.25 kg/m3, EN15804+A2, ref. year 2023	27.061	m3	
	EXTERNAL WALL	Lime paint, 0.15-0.25 kg/m2, 1700-1900 kg/m3, EN15804+A2, ref. year 2021	3.383	m3	
	EXTERNAL WALL	Sand-lime brick, 2000 kg/m3, EN15804+A2, ref. year 2023	29.598	m3	
	EXTERNAL WALL	Extruded polystyrene (XPS), 32 kg/m3, EN15804+A2, ref. year 2023	8.87	m3	
	EXTERNAL WALL	Ready-mix concrete C25/30, C25/30, 2300 kg/m3, EN15804+A2, ref. year 2023	108.66	m2	280
Internal and non-load-bearing walls	INTERNAL WALL	Gypsum interior plaster, 900 kg/m3, EN15804+A2, ref. year 2023	3.44	m3	
	INTERNAL WALL	Sand-lime brick, 2000 kg/m3, EN15804+A2, ref. year 2023	22.844	m3	
	INTERNAL WALL	Galvanized steel stud framing profiles per m2 (air gap included), UD and CD profiles included, wing width: 6 mm, flange width:50 mm, steel thicnkess:0.6 mm (23 gauge), 450 mm spacing, 2.4 kg/m2 (One Click LCA)	516.4	kg	
	INTERNAL WALL	Gypsum plaster board, fire resistant, 12.5 mm, 10 kg/m2, EN15804+A2, ref. year 2023	53.805	m2	12.5
Floor and Horizontal Elements	ROOF	Roof tile, 45 kg/m2, EN15804+A2, ref. year 2021	114.08	m2	
	ROOF	Solid construction timber (15% moisture / 13% H2O content), 529 kg/m3, 15% moisture content, EN15804+A2, ref. year 2023	9.216	m3	
	INSULATION	Dry floor screed, gypsum fiber board, 25 mm, 24.07 kg/m2, 960 kg/m3, EN15804+A2, ref. year 2023	234.59	m2	60
	BEAM	Mineral wool (facade insulation), 46.25 kg/m3, EN15804+A2, ref. year 2023	18.252	m3	
	BEAM	Gypsum wallboard, 100 mm, 84 kg/m2, 840 kg/m3, EN15804+A2, ref. year 2023	114.08	m2	100
	BEAM	Gypsum fiber board, 25 mm, 24.07 kg/m2, 960 kg/m3, EN15804+A2, ref. year 2022	114.08	m2	25
	BEAM	Extruded polystyrene (XPS), 32 kg/m3, EN15804+A2, ref. year 2023	5.948	m3	
	SLAB	Ready-mix concrete C25/30, C25/30, 2300 kg/m3, EN15804+A2, ref. year 2023	32.048	m3	168.31
Stairs	OTHER	Ready-mix concrete C25/30, C25/30, 2300 kg/m3, EN15804+A2, ref. year 2023	0.45	m3	200
Windows and Doors	DOOR	Wooden doors, calculated average for Germany, 1.23x2.18 m, 36 kg/m2, 96 kg/unit (One Click LCA)	21.81	m2	
	WINDOW	Insulated glazing, triple pane, 30 kg/m2, EN15804+A2, ref. year 2023	40.34	m2	

5.4.6.5. LOD 100 ASSUMPTION-BASED QUANTITY TAKEOFF

As discussed in Section 5.4.6.2, performing a material takeoff directly from the LOD 100 model is not possible, since the model consists solely of generic solid mass volumes without any element-level geometric or material definition. Consequently, to conduct an LCA at this stage, a set of simplifying assumptions was required to derive approximate material quantities for each building element category from the limited information available in the mass model, such as the overall gross floor area (GFA), building footprint, and number of floors. Table 20 summarises, for each element category, which quantities could be directly known or derived from the LOD 100 mass model, and which required an additional simplifying assumption.

Table 20 - Element categories and information availability at LOD 100

Element category	Known/derivable at LOD 100
Foundation, sub-surface, basement, retaining walls	GFA footprint, number of underground floors, approximate basement height, assumed foundation type/depth
External walls and facade	Total envelope area, building height, number of above-ground floors, overall footprint/perimeter (via shape factor)
Floor slabs, ceilings, roofing decks, beams, roof	GFA per floor, number of floors, roof type/shape, internal floor height (assumed)
Internal walls and non-bearing structures	Approximate internal wall area (via shape efficiency factor), room count/layout, % load-bearing vs non-load-bearing (assumed)
Other structures (stairs)	Number of staircases, approximate location, footprint
Windows and doors	Assumed window-to-wall ratio (WWR), approximate door count (derived from room count)

Building on these assumptions, Table 21 presents the specific values derived from the mass model and applied assumptions for the case study building. The building's overall footprint was approximated as a rectangle with side lengths of 10 m and 8.5 m, which, together with the building height, was used to estimate the total external envelope area using the shape-factor relationship $A_{wall} = 2H(L1 + L2)(3)$, yielding an envelope area of approximately 222 m². A window-to-wall ratio (WWR) of 0.3 and an internal wall ratio of 0.9, the latter representing the ratio of internal wall area to the total above-ground façade area (comprising external walls, windows, and external doors combined), were both obtained from One Click LCA's Carbon Designer tool, based on the building being specified as a one-dwelling residential unit; these values reflect the tool's internal default estimates for this building typology rather than an independently derived German building standard. Applying the assumed WWR to the estimated envelope area yielded a window area of approximately 66.6 m².

The number of doors was estimated based on the assumed room count derived from the GFA and floor layout assumptions, and door dimensions were assigned according to the DIN 18101 standard for German interior and exterior doors. Standard interior doors, per this standard, are available in leaf widths of 610, 735, 860, 985, 1110, or 1235 mm, with a standard leaf height of 1985 mm; the most common residential interior door size, 860 x 1985 mm (approximately 1.7 m²), was assumed for internal doors in this study. Exterior and entrance doors were assumed to follow typical dimensions of 960-1010 mm in width and 2050-2110 mm in height (approximately 2.0-2.1 m²), consistent with standard German residential entrance door sizing.

Through this combination of derivable geometric information, tool-based default ratios, and standardised dimensional assumptions, an approximate material quantity takeoff was established for

the LOD 100 model, allowing the LCA to be conducted despite the complete absence of detailed material information at this modelling stage.

Table 21 - Derived quantities and assumptions used for the LOD 100 quantity takeoff

Required information	Quantity
GFA	274 m2
Number of above-ground floors	2
Number of underground floors	1
Length 1	10
Length 2	8.5
Height (above ground)	6
Internal floor height	2.5
Number of staircases	1
Envelope Thickness	350 mm
Window-to-Wall ratio	0.3
Window area	66.6 m2
Awall=2H(L1+L2)	222 m2
Doors	6
Slab thickness/foundation	200 mm
Internal wall ratio	0.9

Table 22 – Calculation of Quantities of building parts

BUILDING PART	MATERIAL	QUANTITY	QTY_TYPE	AMOUNT
FOUNDATION	Ready-mix concrete C25/30, C25/30, 2300 kg/m3, EN15804+A2, ref. year 2023	GFA/3 x Slab thickness	m3	18.26
EXTERNAL WALL	Ready-mix concrete C25/30, C25/30, 2300 kg/m3, EN15804+A2, ref. year 2023	Awall x Envelope thickness	M3	77.7
EXTERNAL WALL	Sand-lime brick, 2000 kg/m3, EN15804+A2, ref. year 2023	2 x 3 (L1 +L2)	M3	
INTERNAL WALL	Sand-lime brick, 2000 kg/m3, EN15804+A2, ref. year 2023	Awall x Internal wall ratio x 0.2	m3	39.96

STAIR	Ready-mix concrete C25/30, C25/30, 2300 kg/m3, EN15804+A2, ref. year 2023	0.45	m3	
SLAB	Ready-mix concrete C25/30, C25/30, 2300 kg/m3, EN15804+A2, ref. year 2023	10 x 8.5 x 2	m2	250
ROOF	Solid construction timber (15% moisture / 13% H2O content), 529 kg/m3, 15% moisture content, EN15804+A2, ref. year 2023	10 x 8.5 x 0.2 x 0.08	m3	0.3
WINDOW	Insulated glazing, triple pane, 30 kg/m2, EN15804+A2, ref. year 2023	Awall x Window-to-Wall ratio	m2	66.6
DOOR	Wooden doors, calculated average for Germany, 1.23x2.18 m, 36 kg/m2, 96 kg/unit (One Click LCA)	1.7 x 6	m2	10.2

5.5. DATABASE EXTRACTION AND COMPARISON METHOD

Results were extracted from One Click LCA in Excel format, rather than as a static PDF report, as the Excel export provides greater flexibility for subsequent data processing, custom table design, and the creation of tailored charts and visualisations suited to the specific comparative analysis required by this thesis. The exported Excel file contains results across all 13 environmental impact categories defined under EN 15804 +A2, disaggregated by life cycle stage. However, since all four research questions guiding this thesis are concerned specifically with embodied carbon impacts, rather than the full multi-criteria environmental footprint, the results were narrowed to focus on Global Warming Potential (GWP), specifically GWP Total, GWP Fossil, GWP Biogenic, and GWP LULUC (Land Use and Land Use Change), consistent with the disaggregated GWP reporting introduced under the +A2 standard (see Section 5.4.2). The remaining impact categories (e.g., acidification, eutrophication) were not analysed further, as they fall outside the defined scope of this thesis. However, they remain available within the exported dataset for potential future research. Given that the system boundary of this thesis is already restricted to the A1-A3 production stage (see Section 5.4.5), no further disaggregation by life cycle module was necessary, as no additional life cycle stages were included in the assessment.

Regarding normalisation, dividing GWP results by gross floor area (kg $CO2e/m^2$) is the standard convention in LCA literature when comparing different buildings of varying size, or when benchmarking results against external references such as DGNB benchmarks. However, this normalisation step was not applied in the present study, since the same building and the same gross floor area are held constant across all three LOD-stage models; as the denominator does not vary between models, normalising by GFA would not alter the relative comparison between LOD 100, LOD 200, and LOD 300, and raw GWP totals were therefore used directly.

The comparison across LOD stages was structured to address this thesis's research questions directly. First, to assess the overall deviation in embodied carbon between LOD stages (Research Question i), total GWP values were compared directly across LOD 100, LOD 200, and LOD 300 for the building as a whole. Second, to identify which building elements drive the greatest share of this deviation (Research Question ii), the comparison was repeated at the building part level, using the same element classification applied in the Bill of Materials (Section 5.4.6.4): Foundation and Sub-surface, External Walls and Façade, Internal and Non-Load-Bearing Walls, Stairs, Floor and Horizontal Elements, and Doors and Windows. This element-level comparison further supports Research Question iii, allowing component groups with a

consistently minor contribution to total embodied carbon to be identified as potentially negligible within a BIM-based LCA context.

For both the total building level and each building part, the percentage deviation of LOD 100 and LOD 200 from LOD 300 was calculated using the standard percentage change formula:

$$\Delta\% = \frac{GWP_{LODx} - GWP_{LOD300}}{GWP_{LOD300}} \times 100 \quad (1.3)$$

where GWP_{LODx}refers to the GWP value at either LOD 100 or LOD 200, and GWP_{LOD300} serves as the reference value. LOD 300 was selected as the reference point for this comparison because it represents the most detailed and materially accurate of the three models, incorporating fully layered construction assemblies and refined geometry (see Section 5.3), and therefore constitutes the closest approximation to an as-built representation among the three LOD stages assessed.

To visualise the results of this comparison, column and bar charts were used to display GWP values and percentage deviations across LOD stages, both at the total building level and broken down by building part, allowing patterns of deviation to be identified visually across component groups. The findings of this comparison are further discussed in relation to existing BIM-LCA literature in Chapter [X], addressing Research Question iv.

5.6. VALIDITY AND LIMITATIONS

5.6.1. INTERNAL VALIDITY

Comparing the same building across LOD 100, LOD 200, and LOD 300 gives this study strong internal validity, since the building's overall geometry, gross floor area, and building identity were held constant across all three models, as established in Section 5.3.1. Because these characteristics do not vary between models, any differences observed in the resulting GWP values can be attributed specifically to the level of development applied to individual building elements, rather than to confounding variables arising from differences in the building itself. This internal validity is further reinforced by the consistent structural mapping criteria applied across all three LOD stages: the basement enclosure walls were modelled as concrete throughout, the external walls were modelled as sand-lime brick masonry throughout, and the roof was modelled as an insulated timber rafter construction throughout, as described in Sections 5.3.2 to 5.3.4. In addition, the overall thickness of each of these elements was held constant between LOD 200 and LOD 300, with only the internal layer composition changing between these two stages. This consistency ensures that observed differences in GWP between LOD 200 and LOD 300 stem specifically from increased material and layer specificity, rather than from unrelated changes in material type or overall element dimension. LOD 100 constitutes a partial exception to this pattern, since, as detailed in Section 5.4.6.5, the LOD 100 quantity takeoff relied on a distinct set of simplifying assumptions, including default ratios obtained from One Click LCA's Carbon Designer tool, rather than on the same structural material assumptions applied at LOD 200 and LOD 300.

5.6.2. EXTERNAL VALIDITY

The findings of this study cannot be generalised beyond the specific case study building assessed, meaning the results may not directly transfer to other building typologies, sizes, structural systems, or LCA software tools. This thesis, however, does not aim to produce universally applicable embodied

carbon benchmarks; rather, it aims to demonstrate and evaluate a method, specifically the application of the BIMForum LOD Specification within a BIM-based LCA workflow, using One Click LCA as the calculation platform. As such, the limited generalizability of the specific numerical results should be understood as a deliberate delimitation of scope rather than a methodological flaw, and the study is intended to provide a general, transferable understanding of how the application of this method affects LCA outcomes, rather than to establish fixed benchmark values applicable to other projects.

5.6.3. METHODOLOGICAL LIMITATIONS

Several specific limitations arise from the methodological choices made throughout this study.

First, the quantity takeoff performed at LOD 100 relies heavily on simplifying assumptions, including shape-factor-based geometric estimates and default ratios (window-to-wall ratio and internal wall ratio) obtained from One Click LCA's Carbon Designer tool, rather than on any actual modelled geometry, as detailed in Section 5.4.6.5. While this reflects the genuinely limited information available at this stage of design and therefore constitutes an accurate representation of the kind of uncertainty inherent to LOD 100 assessments in practice, it also means that LOD 100 results carry a fundamentally different, and likely higher, degree of uncertainty than the LOD 200 and LOD 300 results, which were derived from modelled geometry and mapped material data.

Second, the case study building itself was modelled in a relatively simplified manner, and the degree of geometric detail introduced between LOD 200 and LOD 300 was comparatively limited; the primary distinction between these two stages lay in the specificity of construction assembly (i.e., the subdivision of single-layer elements into multi-layer assemblies) rather than in significant changes to overall geometry. Had this methodology been applied to a real, more architecturally complex project, the geometric refinement between LOD 200 and LOD 300 would likely have been more pronounced, potentially resulting in larger observed deviations in GWP between these two stages than were found in this study.

Third, several elements were deliberately simplified across LOD stages for practical reasons, rather than being modelled to their full corresponding LOD definition. As described in Sections 5.3.3 and 5.3.4, the stairs, windows, and doors were modelled identically at LOD 200 and LOD 300, relying on Revit's predefined manufacturer-style families rather than custom-detailed geometry, since these families already exceed the geometric detail required at either stage.

Fourth, reliance on manual, element-by-element material mapping and specific manual adjustments such as deleting door and window sub-components and estimating metal stud quantities from wall geometry (Section 5.4.6.3) introduces a degree of subjectivity into the results, despite the consistent criteria applied across all three models.

Fifth, this study excludes all building services, including plumbing, HVAC, and electrical systems (Section 5.3.7), meaning that the reported GWP results represent only the embodied carbon associated with the structural and architectural elements of the building, not its total embodied carbon impact. This exclusion is consistent with common practice in BIM-based LCA research and was adopted to maintain a manageable modelling scope. Still, it should be understood as narrowing the completeness of the reported results relative to the building's full life cycle impact.

Sixth, the system boundary of this study is restricted to the production stage only (modules A1-A3), as detailed in Section 5.4.5. This boundary corresponds precisely to DGNB indicator 2.5.1 ("CO2-reduziertes Bauwerk – Herstellungsphase"), which evaluates the fossil greenhouse gas emissions (GWPfossil) of a building using only modules A1-A3. It should be noted, however, that DGNB's broader life cycle GWP metric, evaluated separately under indicator 3.1.1 ("Evaluation of further life cycle assessment indicators"), is defined as the sum of modules A1-A3, B4 (replacement), and C3-C4 (end-of-life), rather

than A1-A3 alone [90]. The A1-A3-only boundary adopted in this thesis therefore aligns precisely with DGNB's dedicated manufacturing-phase indicator (2.5.1) but does not capture the additional life-cycle modules assessed separately under indicator 3.1.1. This boundary means that the results do not capture material replacement or end-of-life impacts and should therefore be interpreted as aligned with DGNB's early-design-stage manufacturing-phase indicator specifically, rather than with its complete life cycle GWP assessment.

5.6.4. MITIGATION MEASURES

Despite these limitations, several steps were taken to preserve the validity of the comparison. The same overall building geometry, gross floor area, and core structural material assumptions were held constant across all three LOD models, isolating LOD as the primary variable under investigation. Consistent mapping criteria, database (Ökobaudat), EPD type (generic), and standard compliance (EN 15804 +A2) were applied uniformly across all three models, as described in Section 5.4.6.1, minimising the risk that differences in results stem from inconsistent methodological choices rather than genuine LOD-driven differences. Finally, the same extraction, normalisation, and comparison procedures, described in Section 5.5, were applied identically to all three models, ensuring that the reported percentage deviations reflect actual differences in modelling detail rather than inconsistencies in analysis.

In accordance with MBUILD's AI-use guidelines, AI tools were used throughout this thesis to support brainstorming and structuring of content, to assist with research and identification of relevant literature and standards, to generate certain images and to refine language clarity and style.

6
RESULTS AND DISCUSSION

6.1. INTRODUCTION TO THE ASSESSMENT

This chapter presents the results of the comparative Life Cycle Assessment conducted across the three Levels of Development stages defined in this study, LOD 100, LOD 200, and LOD 300. It discusses these findings in relation to the research questions guiding this thesis. As established in Section 5.5, the embodied carbon impacts reported throughout this chapter are limited to the Global Warming Potential (GWP) indicators defined under EN 15804 +A2, specifically GWP Fossil and GWP Total for the life Cycle A1-A3, with the remaining twelve impact categories excluded as outside the defined scope of this thesis.

Both GWP Fossil and GWP Total are reported throughout this chapter, though they serve distinct analytical purposes. GWP Fossil is treated as the primary indicator for comparative and benchmarking purposes, since it is the metric explicitly used by the DGNB certification system when assessing greenhouse gas emissions for modules A1-A3, and since it excludes the biogenic carbon storage and release effects associated with wood-based materials, thereby providing a more methodologically consistent basis for comparison both across LOD stages and against external benchmarks and literature. GWP Total, which additionally incorporates biogenic and land-use-related carbon effects, is reported alongside GWP Fossil as a secondary, diagnostic indicator, allowing any divergence between the two metrics, particularly for timber-containing building elements such as the roof structure, to be identified and discussed.

The results are structured around two complementary levels of comparison. First, an overall building-level comparison (Section 6.2) evaluates total GWP Fossil and GWP Total values across LOD 100, LOD 200, and LOD 300 for the building as a whole, addressing Research Question i concerning the overall magnitude of deviation in embodied carbon between LOD stages. Second, an element-by-element comparison (Sections 6.3) examines the same indicators at the level of individual building part categories, consistent with the classification established in the Bill of Materials (Section 5.4.6.4): Foundation and Sub-Surface, External Walls and Façade, Floor Slabs and Roof, Internal Walls and Non-Load-Bearing Structures, Windows and Doors, and Other Structures and Materials (Stairs). This element-level comparison addresses Research Question ii, concerning which building elements drive the greatest share of the observed deviation, and Research Question iii, concerning whether certain component groups can be considered negligible in BIM-based LCA due to their consistently minor contribution to total embodied carbon.

Following the individual element sections, a cross-element synthesis (Section 6.4) consolidates these findings into a single comparative overview, before the results are benchmarked against published literature and DGNB reference values (Section 6.5) to address Research Question iv. The chapter

concludes with a discussion of the limitations affecting the interpretation of these results (Section 6.6) and their implications for BIM-based LCA practice (Section 6.7).

6.2. OVERALL BUILDING-LEVEL COMPARISON

Table 23 presents the total GWP Fossil and GWP Total results for the case study building at each of the three assessed LOD stages, alongside the percentage deviation of LOD 100 and LOD 200 from LOD 300, calculated using the percentage change formula introduced in Section 5.5.

Table 23 - Whole-building embodied carbon (GWP Fossil and GWP Total) by LOD stage

LOD Stage	GWP Fossil (kg CO2e)	GWP Total (kg CO2e)	Deviation Fossil from LOD 300	Deviation Total from LOD 300
LOD 100	64,063.56	63,437.25	-5.1%	-3.4%
LOD 200	61,463.85	52,977.78	-9.0%	-19.3%
LOD 300	67,531.77	65,669.54	reference	reference

At the whole-building level, both GWP Fossil and GWP Total increase progressively from LOD 200 to LOD 300, consistent with the expectation that greater modelling detail and material specificity yield higher, more complete embodied carbon estimates. GWP Fossil shows a moderate deviation of -9.0% at LOD 200 relative to LOD 300, whereas GWP Total shows a substantially larger deviation of -19.3%, indicating that the gap between these two stages is considerably more pronounced when biogenic and land-use-related carbon effects are included in the reported figure.

This divergence between the two indicators is directly relevant to Research Question i, since it suggests that the magnitude of deviation observed between LOD stages is sensitive to which GWP indicator is used for the comparison, rather than being a fixed, indicator-independent quantity. A likely explanation, examined further in the element-level sections that follow, is that timber-based elements introduced or refined between LOD 200 and LOD 300, such as the roof structure, carry a biogenic carbon credit that is captured in GWP Total but excluded from GWP Fossil, amplifying the apparent deviation when Total is used.

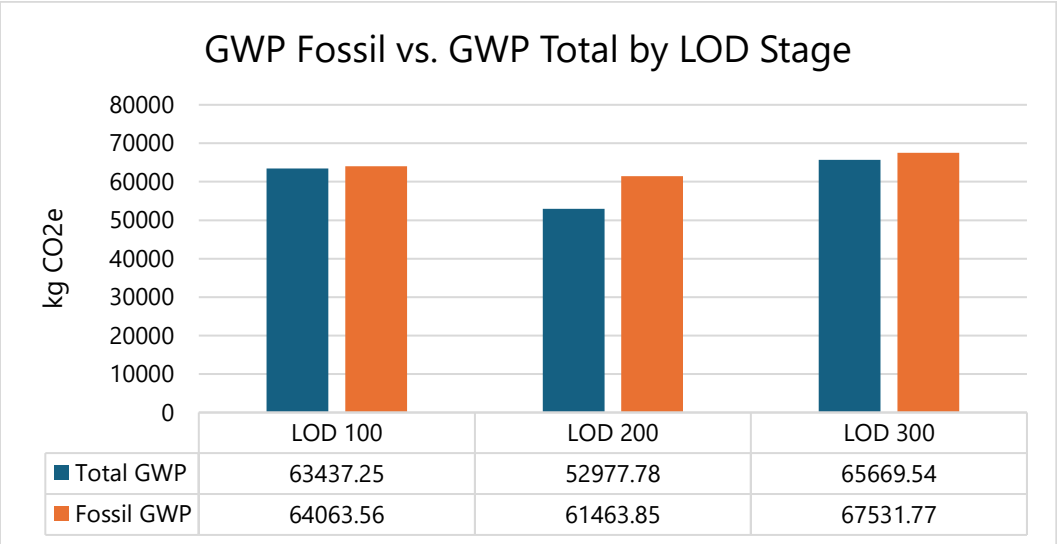


Figure 17 - Total building GWP Fossil and GWP Total across LOD 100, LOD 200, and LOD 300

Notably, LOD 100 shows a smaller deviation from LOD 300 than LOD 200 does for both indicators, at 5.1% for Fossil and -3.4% for Total, despite LOD 100 relying entirely on assumption-based quantity takeoff rather than modelled geometry (Section 5.4.6.5). This counterintuitive result, where the least detailed model produces a total closer to the most detailed reference than the intermediate model does, warrants closer examination at the element level, since it may indicate that the simplifying assumptions used at LOD 100 happened to offset each other at the whole-building scale, even though individual element-level results, discussed in the sections that follow, may show substantially larger errors in either direction.

When normalised by gross floor area (274 m^2), the LOD 300 reference case yields approximately 246.5 kg CO2e/m^2 for GWP Fossil and 239.7 kg CO2e/m^2 for GWP Total, both of which fall within the plausible range established against external benchmarks in Section 6.5.

6.3. ELEMENT-BY-ELEMENT COMPARISON

6.3.1. FOUNDATION, SUB-SURFACE, BASEMENT

Table 24 presents the GWP Fossil and GWP Total results for the Foundation, Sub-Surface and Basement category across the three LOD stages.

Table 24 - GWP Fossil and GWP Total by LOD stage: Foundation, Sub-Surface and Basement

LOD Stage	GWP Fossil (kg CO2e)	GWP Total (kg CO2e)	Deviation Fossil from LOD 300	Deviation Total from LOD 300
LOD 100	4,049.26	4,047.45	-28.7%	-28.7%
LOD 200	6,078.20	6,075.61	+7.0%	+7.0%
LOD 300	5,680.19	5,677.74	reference	reference

Unlike the whole-building results discussed in Section 6.2, GWP Fossil and GWP Total are nearly identical for this element category at every LOD stage, with deviations matching to within 0.1 percentage points. This near-total overlap is consistent with the expectation that foundation and basement elements, modelled as concrete throughout all three LOD stages (Section 5.6.1), contain negligible biogenic or land-use-related carbon content, since concrete is a fossil-dominated material with no meaningful wood or bio-based component.

LOD 100 shows a substantial underestimation of -28.7% relative to LOD 300, which is consistent with this category relying on the most simplified assumption chain in the LOD 100 takeoff, where foundation depth and type were assumed rather than derived from any modelled geometry (Section 5.4.6.5).

LOD 200, by contrast, shows a moderate overestimation of +7.0% relative to LOD 300, indicating that the transition from LOD 200 to LOD 300 for this element involved a net reduction in embodied carbon. Unlike most other element categories in this study, this deviation was not driven by increased layer specificity alone, but by an actual change in foundation type between the two stages. At LOD 200, the foundation was modelled as a mat foundation with a uniform thickness of 300 mm and a continuous slab that also served as the basement floor, meaning the full footprint area was counted as foundation volume. At LOD 300, this was revised to a strip footing running beneath the load-bearing walls only, with an increased thickness of 400 mm to reflect a more realistic structural detail. At the same time, the basement floor was retained as a separate concrete slab still classified within the foundation category to preserve consistency with the LOD 200 scope.

Because the strip footing occupies a substantially smaller total volume than a continuous mat foundation covering the entire footprint, this change in foundation type reduced the overall concrete quantity at LOD 300, despite the increase in footing thickness, even though the basement slab remained included in both stages on a like-for-like basis. This deviation therefore reflects a genuine refinement toward a more realistic structural system, moving from a simplified continuous mat assumption at LOD 200 to a more construction-representative strip footing arrangement at LOD 300, rather than a change in what is counted within the foundation category.

Taken together, this element category illustrates that GWP Fossil and GWP Total converge closely for concrete-dominated structural elements, meaning the foundation category does not drive the divergence observed at the whole-building level in Section 6.2, and the analysis in the following sections should instead focus on timber-containing elements to identify the source of that divergence.

6.3.2. EXTERNAL WALLS AND FAÇADE

Table 25 presents the GWP Fossil and GWP Total results for the External Walls and Façade category across the three LOD stages.

Table 25 - GWP Fossil and GWP Total by LOD stage: External Walls and Façade

LOD Stage	GWP Fossil (kg CO2e)	GWP Total (kg CO2e)	Deviation Fossil from LOD 300	Deviation Total from LOD 300
LOD 100	32,801.48	32,830.34	+33.0%	+32.8%
LOD 200	22,453.95	22,489.44	-9.0%	-9.0%
LOD 300	24,669.04	24,720.12	reference	reference

As with the foundation category, GWP Fossil and GWP Total are nearly identical at every LOD stage for external walls, differing by less than 0.2 percentage points. This is consistent with the external wall assembly being modelled as sand-lime brick masonry throughout all three LOD stages (Section 5.6.1), a material with negligible biogenic carbon content, meaning the choice of indicator has essentially no bearing on the interpretation of results for this element category.

LOD 100 shows a large deviation, overestimating GWP by approximately 33% relative to LOD 300, in sharp contrast to the underestimation seen for the foundation category in Section 6.3.1. This is a critical finding for Research Question ii, since it demonstrates that LOD 100 assumption errors are not uniformly directional across element categories. Some categories are underestimated, and others substantially overestimated, meaning these errors do not simply cancel out predictably at the whole-building level. This helps explain the counterintuitive whole-building result noted in Section 6.2, where LOD 100 appeared closer to LOD 300 than LOD 200 did, since large offsetting errors across categories, a strong overestimation in external walls counterbalancing a strong underestimation in foundations, can produce a deceptively small net deviation at the aggregate level despite substantial errors at the element level.

The LOD 100 overestimation is most plausibly attributable to the shape-factor-based envelope area estimation method described in Section 5.4.6.5, where wall area was derived from a simplified rectangular footprint and assumed height rather than actual modelled geometry, likely overestimating the true envelope surface area and, consequently, the associated material quantity.

LOD 200 underestimates GWP by approximately 9% relative to LOD 300, a moderate deviation that, unlike most categories in this study, is not attributable to a shift from a homogeneous to a layered representation, since the exterior wall was already modelled as a three-layer compound assembly at LOD

200, consistent with the BIMForum classification into exterior wall construction, interior skin, and veneer (Section 5.3). Rather, this deviation stems from a refinement in individual layer thicknesses between the two stages. While the structural brick layer remained constant at 175 mm across both stages, the insulation layer thickness increased substantially from 100 mm at LOD 200 to 160 mm at LOD 300, a 60% increase, and the exterior finish layer increased modestly from 15 mm to 20 mm. LOD 200 relied on approximate, non-finalised layer thicknesses. At the same time, LOD 300 reflected the confirmed as-designed dimensions; this increase in insulation and finish thickness at LOD 300 directly accounts for the higher material quantity, and consequently the higher GWP, observed at this stage.

This element category (External Wall) reinforces the finding from Section 6.3 that GWP Fossil and GWP Total track closely for non-biogenic structural materials. However, it also shows that LOD 100 assumption errors vary substantially across different building element categories, and can even invert in direction. This supports the relevance of the element-level comparison for Research Question ii.

The External Wall category also illustrates a deviation mechanism that is distinct from windows and doors (Section 6.3.6). In that earlier case, deviation was driven by an expansion of material scope during LCA mapping, not by geometric modelling differences. Here, by contrast, the deviation arises purely from thickness refinement within an already-consistent layer structure. This isolates layer-level dimensional precision, rather than material scope, as the specific driver of change between LOD 200 and LOD 300 for this element.

6.3.3. FLOOR AND HORIZONTAL ELEMENTS

Table 26 presents the GWP Fossil and GWP Total results for this category across the three LOD stages.

Table 26 - GWP Fossil and GWP Total by LOD stage: Floor and Horizontal Elements

LOD Stage	GWP Fossil (kg CO2e)	GWP Total (kg CO2e)	Deviation Fossil from LOD 300	Deviation Total from LOD 300
LOD 100	7,604.14	7,347.52	-59.6%	-59.8%
LOD 200	20,624.52	12,964.12	+9.6%	-29.0%
LOD 300	18,814.82	18,257.27	reference	reference

This category shows the clearest divergence between GWP Fossil and GWP Total observed so far in this chapter, particularly at LOD 200, where GWP Fossil overestimates LOD 300 by +9.6%. At the same time, GWP Total underestimates it by -29.0%, a gap of nearly 39 percentage points between the two indicators for the same LOD comparison. This divergence is consistent with the presence of the insulated timber rafter roof construction, modelled consistently as timber throughout all three LOD stages (Section 5.6.1), since wood-based materials carry a negative biogenic carbon contribution in GWP Total that is excluded from GWP Fossil, meaning the two indicators can move in different directions relative to one another as the proportion or specification of timber material changes between LOD stages.

At LOD 100, both indicators show a very large underestimation of approximately -60% relative to LOD 300, the most severe deviation observed for any element category examined in this chapter. This is consistent with the LOD 100 quantity takeoff relying on a simplified assumption-based approach rather than any detailed layered assembly (Section 5.4.6.5): floor slabs were quantified only as ready-mix concrete, derived by multiplying the building's area by two to account for both slab levels, while the roof was quantified as solid construction timber based on an assumed 8% coverage of the roof area, a simplified approximation of the actual rafter coverage ratio later refined at LOD 300. Notably, LOD 100 did not include any of the insulation, finish, or additional structural layers present in the LOD 200 and

LOD 300 assemblies, since these layers could not be derived from the mass model without detailed assembly information, meaning the LOD 100 quantity takeoff captured only the two primary structural materials (concrete slabs and roof timber) rather than the full multi-layer buildup applied from LOD 200 onward. This absence of insulation and finish layers, rather than any error in the structural material quantities themselves, is the most likely primary driver of the severe underestimation observed at this stage.

At LOD 200, the sign reversal between GWP Fossil (overestimate) and GWP Total (underestimate) is the most significant finding in this section, since it demonstrates that reporting only one of these two indicators would have led to an entirely different conclusion about whether LOD 200 over- or underestimates embodied carbon for this element category. This directly supports the decision, established in Section 6.1, to report both indicators throughout this chapter, and it directly answers part of Research Question ii by identifying the roof and floor category as the primary driver of the Fossil-Total divergence already observed at the whole-building level in Section 6.2.

The difference in the results from LOD 200 to LOD 300 is mainly attributable to a correction applied to the timber quantity takeoff to account for the discrete, non-continuous nature of rafter construction, since the insulation, finish, and concrete slab layers were modelled identically at both stages. At LOD 200, the roof's timber joist/rafter layer was quantified by taking Revit's reported 80 mm layer thickness at face value across the entire roof area, effectively treating the layer as a continuous solid timber slab. At LOD 300, this assumption was corrected. Since rafters are discrete structural members spaced at regular intervals rather than a continuous solid layer, the actual timber volume was recalculated using a standard rafter width of 47 mm and centre-to-centre spacing of 600 mm, yielding a timber coverage ratio of 7.83 per cent of the total roof area. Applied to the 114 m^2 roof area and 80 mm layer thickness, this produced a corrected timber volume of approximately 0.71 m^3 (377.92 kg) at LOD 300, substantially lower than the 9.12 m^3 (approximately 4,824 kg) that would result from treating the layer as fully solid, as was effectively done at LOD 200. This correction represents a methodological refinement toward a more physically accurate representation of timber-frame construction, directly paralleling the equivalent correction applied to the metal stud partition quantities (Section 5.4.6.3), rather than reflecting any change in material scope or additional layers. Because this correction substantially reduces the biogenic-heavy timber mass counted at LOD 300 relative to the uncorrected LOD 200 quantity, it directly explains why GWP Fossil does not rise from LOD 200 to LOD 300 while GWP Total falls, since the reduction in timber volume disproportionately affects the biogenic carbon credit embedded in the Total indicator relative to the smaller, non-biogenic fossil contribution.

This finding also has a clear implication for Research Question iii: rather than being a negligible category, floor and roof elements emerge as one of the most volatile and indicator-sensitive categories in this assessment, and should be flagged as requiring particular caution in BIM-based LCA workflows involving timber construction, especially when only a single GWP indicator is reported, and especially when quantity takeoffs risk overestimating timber volume by failing to account for the discrete, non-continuous geometry of rafter or joist-based assemblies.

6.3.4. INTERNAL WALLS AND NON-BEARING STRUCTURES

Table 27 presents the GWP Fossil and GWP Total results for the Internal Walls and Non-Load-Bearing Structures category across the three LOD stages.

Table 27- GWP Fossil and GWP Total by LOD stage: Internal Walls and Non-Bearing Structures

LOD Stage	GWP Fossil (kg CO2e)	GWP Total (kg CO2e)	Deviation Fossil from LOD 300	Deviation Total from LOD 300
LOD 100	14,925.80	14,945.94	+59.3%	+59.8%
LOD 200	8,536.30	8,554.96	-8.9%	-8.5%
LOD 300	9,369.34	9,353.92	reference	reference

As with the foundation and external wall categories, GWP Fossil and GWP Total remain closely aligned at every LOD stage for internal walls, differing by less than half a percentage point. This is consistent with internal partitions being modelled using metal stud and sand-lime brick masonry rather than timber, meaning biogenic carbon effects are negligible for this category, similar to the pattern already established for the foundation (Section 6.3.1) and external wall (Section 6.3.2) categories.

LOD 100 shows a very large overestimation of approximately +59% relative to LOD 300, a striking contrast to the underestimation seen for floor and roof elements in Section 6.3.3. Since internal walls were not modelled at all at LOD 100, consistent with the solid mass modelling approach adopted at this stage, this entire result derives from an assumption-based estimation rather than any geometric quantity: internal wall area was estimated using an internal wall ratio of 0.9 obtained from One Click LCA's Carbon Designer tool (Section 5.4.6.5), applied as a fixed proportion of total façade area rather than derived from an actual room-by-room layout, and the resulting area was assumed to consist entirely of masonry construction with a uniform thickness of 200 mm. This combination of an unverified area ratio and a uniform masonry-only thickness assumption appears to have substantially overstated the true quantity of internal partitions for this case study building, and illustrates why internal walls are particularly difficult to estimate reliably at LOD 100: unlike the building envelope, which can be reasonably approximated from overall footprint and height, internal partition layout is inherently a room-level design decision with no reliable proxy derivable from massing-level information alone.

LOD 200 shows a moderate underestimation of approximately -9% relative to LOD 300. Unlike the LOD 100 to LOD 300 comparison, this deviation is not driven by a change in overall wall thickness, since the structural layer thickness for each wall type, 210 mm for load-bearing masonry, 150 mm for non-load-bearing masonry, and 95 mm for metal stud partitions, was already set at LOD 200 to match the corresponding LOD 300 structural thickness. Instead, two distinct factors specific to this category account for the deviation. First, the addition of finish layers at LOD 300, a 15 mm plaster layer on each side of both masonry wall types and a 12.5 mm gypsum wallboard layer on each side of the metal stud partition, increased the total wall thickness and therefore the total material volume at LOD 300 relative to the structural-only LOD 200 assembly. Second, and more significantly for the metal stud partition specifically, the stud spacing assumption was refined from a generic 600 mm centre-to-centre spacing at LOD 200 to the actual specified 500 mm centre-to-centre spacing at LOD 300, increasing the number of studs required for the same 17.3125 m wall run from 30 to 36. The total stud mass increased from 442.6 kg to 531.2 kg, an increase of approximately 20 per cent, using the same generic Ökobaudat reference product (6.5 kg/m) at both stages (Table 17). This stud spacing correction closely parallels the rafter coverage correction applied to the roof structure in Section 6.5, in that both reflect a refinement of an assumed spacing parameter as design certainty increased, rather than the introduction of new material scope.

This category adds further evidence to the pattern already emerging across Sections 6.3.1 to 6.3.4: LOD 100 errors vary dramatically in both magnitude and direction depending on which simplifying assumption drives the element category, ranging from -60% (floor/roof) to +59% (internal walls) within the same model. This strongly supports the argument for Research Question iii that no element category

can be assumed negligible by default in a LOD 100 assessment, since the direction and severity of error are assumption-specific rather than predictable from element type alone. This variability across categories is precisely what produces the smaller, offsetting net deviation observed at the whole-building level in Section 6.2. Furthermore, the LOD 200 to LOD 300 deviation in this category, like the roof rafter correction in Section 6.3.2, illustrates that spacing or interval-based structural systems (studs, rafters) are particularly sensitive to refinement of assumed spacing parameters, a mechanism distinct from both the pure thickness refinement seen in external walls (Section 6.3.2) and the material scope expansion seen in windows and doors (Section 6.3.6).

6.3.5. OTHER STRUCTURES (STAIRS)

Table 28 presents the GWP Fossil and GWP Total results for the Other Structures and Materials category, which encompasses stairs, across the three LOD stages.

Table 28 - GWP Fossil and GWP Total by LOD stage: Stairs

LOD Stage	GWP Fossil (kg CO2e)	GWP Total (kg CO2e)	Deviation Fossil from LOD 300	Deviation Total from LOD 300
LOD 100	99.57	99.52	-86.3%	-86.3%
LOD 200	99.79	99.75	-86.3%	-86.3%
LOD 300	728.04	727.11	reference	reference

GWP Fossil and GWP Total are again nearly identical across all three LOD stages, differing by well under 0.1 percentage points, consistent with stairs being modelled using non-biogenic materials such as concrete and steel. This category also stands out for a distinctive pattern: LOD 100 and LOD 200 produce almost identical absolute values (99.57 and 99.79 kg CO2e), both deviating from LOD 300 by an essentially identical -86.3%.

This near-equal outcome between LOD 100 and LOD 200 is not the result of a separate LOD 100 estimate. It is simply a result of how this category was handled. Stairs were not included in the LOD 100 model at all, following the general rule that LOD 100 leaves out elements not needed for a rough overall shape (Section 5.6.3). There was also no reliable way to guess a stair quantity at this early stage. So the LOD 200 concrete volume was reused as a stand-in for the LOD 100 value.

Because of this, the LOD 100 result for this category should not be treated as a real test of LOD 100 accuracy. The -86.3% deviation reported for LOD 100 is the same as the LOD 200 deviation, simply because the same number was used for both, not because it was worked out independently.

For this element category, the more useful comparison is between LOD 200 and LOD 300. This comparison reflects a real change between stages, the addition of railings and stringers, rather than a copied number

At LOD 200, stairs were modelled with a basic level of geometric detail, represented simply by risers and treads, using a defined concrete volume. At LOD 300, this same concrete volume was retained unchanged, while railings and stringers were added to increase structural and visual detail, without any further refinement of the stair geometry itself. Of these two additions, the steel railing is the primary driver of the observed sevenfold increase in GWP at LOD 300, since steel carries a substantially higher embodied carbon factor per unit mass than concrete; the stringers, by contrast, were added simply as additional concrete volume and therefore contribute comparatively little to the overall increase, given that the concrete quantity for risers and treads was already established at LOD 200. This distinction is

analytically useful, since it shows that the LOD 200 to LOD 300 deviation for this category is not attributable to structural detailing in general, but specifically to the introduction of a new, higher-carbon material (steel) that was absent from the LOD 200 material scope, rather than to any change in the concrete-based components already present at the earlier stage.

This represents a distinct deviation mechanism identified in this chapter, alongside the pure thickness refinement seen in external walls (Section 6.3.2) and the spacing-parameter refinement seen in internal walls and roof structure (Sections 6.3.3–6.3.4): here, the deviation stems from the introduction of an entirely new, more carbon-intensive material at LOD 300, closely paralleling the mapping-scope expansion identified for windows and doors (Section 6.3.6), where new sub-components were similarly absent from the LOD 200 material scope.

This category is the strongest candidate in this chapter for the "negligible category" question in Research Question iii. Its absolute contribution to total embodied carbon is very small at every LOD stage: under 1,000 kg CO2e, compared to a whole-building total of over 60,000 kg CO2e. This is true even though its percentage deviation is large. This shows an important difference between two ideas: being negligible in absolute terms and being volatile in relative terms. This difference should be carried into the cross-element synthesis. One point to keep in mind: the LOD 100 figure for this category carries limited analytical weight, because it was imputed from the LOD 200 concrete volume, as explained above.

6.3.6. WINDOWS AND DOORS

Table 29 presents the GWP Fossil and GWP Total results for the Windows and Doors category across the three LOD stages.

Table 29 - GWP Fossil and GWP Total by LOD stage: Windows and Doors

LOD Stage	GWP Fossil (kg CO2e)	GWP Total (kg CO2e)	Deviation Fossil from LOD 300	Deviation Total from LOD 300
LOD 100	4,583.33	4,166.48	-44.6%	-39.9%
LOD 200	3,671.05	2,793.9	-55.6%	-59.7%
LOD 300	8,270.34	6,933.38	reference	reference

This category shows a consistent gap between GWP Fossil and GWP Total at every LOD stage, with GWP Total running roughly 8–17% below GWP Fossil in absolute terms. This divergence is attributable to the door panels, which were modelled as wooden doors, and therefore carry a biogenic carbon credit under GWP Total that is excluded from GWP Fossil, consistent with the divergence mechanism identified for the timber roof structure in Section 6.3.3, though considerably smaller in magnitude here given the comparatively limited quantity of timber involved in door panel construction relative to the roof assembly. The window glazing and frame components, along with the door frame and hardware, are not biogenic materials, meaning the door panel is the sole source of this Fossil-Total divergence within the category. Unlike the floor/roof category, the two indicators do not diverge in direction here: both show substantial underestimation at LOD 100 and LOD 200 relative to LOD 300. However, the magnitude of underestimation is consistently larger for GWP Total than for GWP Fossil, since the wooden door panel's biogenic credit is present at every LOD stage and scales proportionally with the underlying quantity error.

Both LOD 100 and LOD 200 substantially underestimate this category relative to LOD 300, with LOD 200 showing an even larger deviation (-55.6 to -59.7%) than LOD 100 (-39.9 to -44.6%), an unusual pattern not seen in any other element category examined so far, where the intermediate LOD stage produces a

worse estimate than the least detailed one. Although the same predefined Revit families were used to model doors and windows at both LOD 200 and LOD 300 for practical modelling purposes, the BIM Forum LOD specification defines LOD 200 for exterior windows (B2020) and exterior doors (B2050) as requiring only a generic object. In contrast, LOD 300 explicitly requires the door panel and frame, and the window's specific type, size, and opening direction, to be defined. Accordingly, the material mapping process (Section 5.4.6.3) was aligned with this specification: only the door panel and window glazing were included in the material takeoff at LOD 200, consistent with the generic-object requirement at this stage, while the frame components were added to the material takeoff at LOD 300, consistent with the BIM Forum [31] requirement for specific panel and frame detail at this stage. The increase from LOD 200 to LOD 300 therefore reflects a genuine, LOD-defined expansion of specification detail, implemented through the material mapping stage rather than through a change in the underlying modelled geometry. It is not an arbitrary methodological artefact independent of the LOD framework.

This finding matters for Research Question ii. It shows that a jump in LOD detail does not always come from a change in the model's geometry. In this case, the same detailed door and window family, frame included, was used in the Revit model at both LOD 200 and LOD 300. The geometry itself never changed between stages. What changed was a mapping decision made during LCA data extraction: the frame was deliberately excluded at LOD 200, in line with the BIM Forum LOD definition, and included at LOD 300. This shows that LOD-driven changes in embodied carbon results can come from scope decisions made outside the model, not only from edits to the geometry itself

6.4. CROSS-ELEMENT SYNTHESIS

Table 30 consolidates the percentage deviations for GWP Fossil and GWP Total across all six building part categories, alongside each category's share of total LOD 300 GWP Fossil, providing a combined view of both the direction of deviation and its practical significance at the whole-building scale.

Table 30 Cross-element deviation and GWP Fossil contribution share by LOD stage

Category	LOD 100 Fossil Dev.	LOD 200 Fossil Dev.	LOD 100 Total Dev.	LOD 200 Total Dev.
Foundation	-28.7%	+7.0%	-28.7%	+7.0%
External Walls	+33.0%	-9.0%	+32.8%	-9.0%
Floor/Roof	-59.6%	+9.6%	-59.8%	-29.0%
Internal Walls	+59.3%	-8.9%	+59.8%	-8.5%
Windows/Doors	-44.6%	-55.6%	-39.9%	-59.7%
Stairs	-86.3%	-86.3%	-86.3%	-86.3%

This consolidated view reveals two clearly distinguishable mechanisms driving deviation across LOD stages, addressing Research Question ii directly. Assumption-driven deviation dominates LOD 100, where errors swing dramatically in both magnitude and direction (from -86.3% for stairs to +59.3% for internal walls), reflecting the fact that each category relies on a distinct simplifying assumption (shape factor, window-to-wall ratio, internal wall ratio) rather than a single consistent source of bias. By contrast, the LOD 200 to LOD 300 transition is driven by a mix of dimensional refinement and specification-driven scope expansion: deviations remain moderate for categories where only layer thickness or spacing was refined (-9 percent for external walls, -8.9 percent for internal walls), but become substantially larger for windows and doors (-55.6 to -59.7 percent), where the deviation reflects the BIM Forum LOD 300

requirement to specify door and window frame detail, implemented in this study through an expansion of the material mapping scope, rather than a change in modelled geometry.

A further pattern emerges when looking at direction rather than magnitude alone. For GWP Total, five of the six categories increase in value between LOD 200 and LOD 300, with Foundation as the only exception. For GWP Fossil, four of six categories increase, with Foundation and Floor/Roof both decreasing. This contrasts with the LOD 100 to LOD 300 comparison, where direction varied unpredictably across categories. The consistency of increase at the LOD 200 to LOD 300 stage suggests that later-stage refinement tends to reveal previously unaccounted material scope (such as door and window frames, or stair railings and stringers) rather than correcting an overestimate. In contrast, LOD 100 assumptions can err in either direction depending on the simplifying method used for that category.

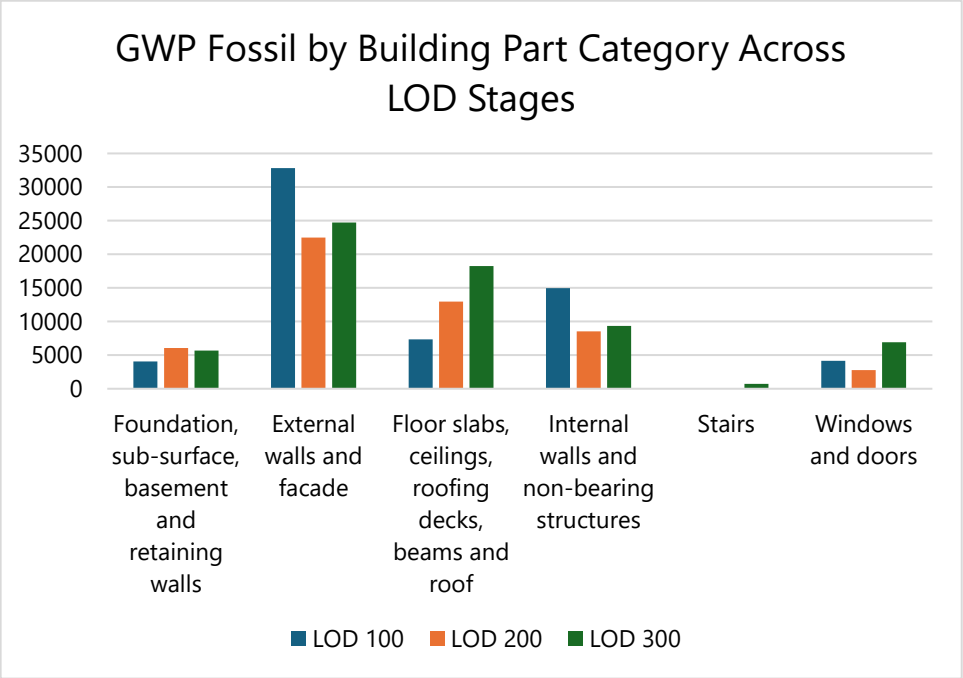


Figure 18 - GWP Fossil by building part category across LOD 100, LOD 200, and LOD 300

The comparison confirms that Floor/Roof is the only category showing a meaningful sign or magnitude divergence between GWP Fossil and GWP Total, with LOD 200 deviation of +9.6% for Fossil versus -29.0% for Total, a nearly 39 percentage point gap attributable to the timber rafter roof's biogenic carbon credit. All other categories show Fossil and Total deviations within roughly 5 percentage points of each other, confirming that biogenic effects are highly localised to timber-containing elements rather than distributed evenly across the building.

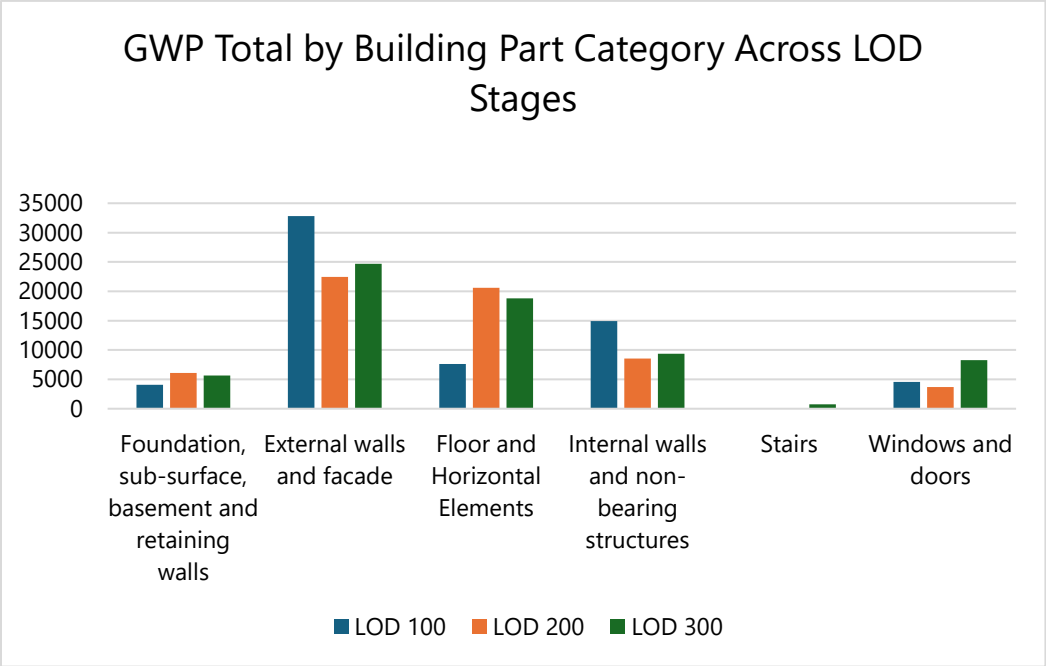


Figure 19 - GWP Total by building part category across LOD 100, LOD 200, and LOD 300

Based on each category's share of total LOD 300 GWP Fossil, only Stairs can reasonably be considered negligible, contributing just 1.1% of total embodied carbon, despite exhibiting the largest percentage deviation of any category (-86.3%); this confirms that negligibility, as defined by Research Question iii, is determined by a category's absolute contribution to total embodied carbon, not by the size of its deviation across LOD stages. External Walls, by contrast, contribute the largest share of total GWP (36.5%) and therefore cannot be considered negligible under any interpretation. The remaining four categories, Floor/Roof (27.9%), Internal Walls (13.9%), Windows/Doors (12.2%), and Foundation (8.4%), all contribute a meaningful share of total embodied carbon and likewise cannot be treated as negligible.

There is another point to note here, separate from the negligibility question. Several of these non-negligible categories (notably Floor/Roof and Windows/Doors) also show high deviation across LOD stages when we follow the BIM Forum definition. This means they are both significant contributors to total embodied carbon and comparatively unreliable to estimate accurately at lower LOD stages. For Floor/Roof, this high deviation is driven mainly by the timber roof structure, since the coarser approximation methods used at lower LOD stages (the flat-layer assumption and the 8% ratio estimate) do not capture the timber rafters' actual quantity and biogenic carbon behaviour as precisely as the LOD 300 calculation does. For Windows/Doors, the deviation stems from the frame inclusion decision discussed earlier: the same detailed door and window geometry was used throughout, but the frame's material was deliberately excluded at LOD 200 and included at LOD 300, in line with the BIM Forum LOD definition.

This combination matters in practice. If a category is both a large contributor to total embodied carbon and unreliable to estimate at early LOD stages, then practitioners who rely on early-stage BIM-LCA workflows are at real risk of getting a meaningfully wrong result for that category, one that will noticeably affect the whole-building total, not just a minor rounding difference.

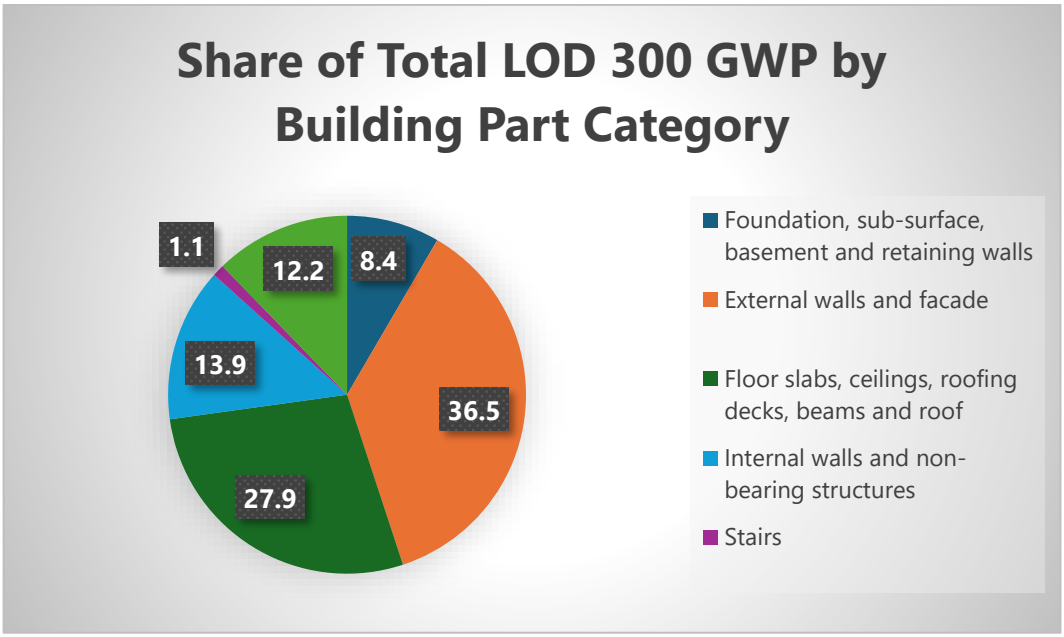


Figure 20 - Share of total LOD 300 GWP Fossil by building part category

6.5. COMPARISON WITH EXISTING BIM-LCA LITERATURE AND DGNB BENCHMARKS

This section addresses Research Question iv by comparing the findings of this study, both the whole-building and element-level deviation patterns identified in Sections 6.2 to 6.4, against existing BIM-LCA research conducted across different Levels of Development, as well as against external DGNB and literature-based benchmarks for A1-A3 embodied carbon.

6.5.1. COMPARISON WITH WHOLE-BUILDING LOD DEVIATION STUDIES

This study found a -9.0% underestimation of GWP Fossil at LOD 200 relative to LOD 300 and a 19.3% underestimation of GWP Total. Three other studies offer useful points of comparison, though each measures things a little differently.

Hollberg et al. [29] did not use a formal LOD framework in his research. They tracked embodied GWP across 34 weekly BIM snapshots of a real office building as it naturally evolved, without assigning LOD tiers to any snapshot. They found that GWP at the peak snapshot (week 8) was twice as high as in the final building, an overestimation caused by placeholder materials, overlapping layers, and quantity errors, not genuine design refinement. This differs from this thesis, where LOD 100 and LOD 200 followed defined, documented assumptions (Section 5.4.6.5) rather than provisional placeholder geometry.

Cavalliere et al. [67] offer the closest comparison, since they explicitly link five design phases to LOD tiers (LOD 100, 200, 300, 400) using Swiss GWP data. Their whole-building GWP values are:

- LOD 100: 10.13 kg CO2-eq/m^2/yr
- LOD 200: 9.27 kg CO2-eq/m^2/yr
- LOD 300: 7.84 kg CO2-eq/m^2/yr

This gives a +29.2% overestimation at LOD 100 relative to LOD 300, and a +18.2% overestimation at LOD 200 relative to LOD 300. Both are opposite in direction to the -9.0% underestimation found in this study. Cavalliere et al. explain this by showing that each phase's result falls within the variability range of the previous phase, largely because their early-stage values are based on averaged data from a predefined component catalogue, which tends to push results upward. This thesis instead built LOD 100 and LOD 200 values from defined assumptions tied to actual geometry, which can push results downward when components are missing entirely rather than averaged.

Rezaei et al. [74] compared LOD 100 and LOD 300 for a residential building in Québec, but reported results only as normalised impact scores, not as a single percentage. Their key finding is qualitative: the LOD 300 result falls within the uncertainty range generated by a Monte Carlo simulation of the LOD 100 assumptions. This supports treating early-stage results as a range rather than one fixed number. This thesis did not apply this kind of probabilistic treatment, which is a limitation worth noting given the large swings found at LOD 100 here (Section 6.9), from +59.3% for internal walls to -59.6% for floor and roof elements.

Nawrocka et al. [75] compared LOD 200 against a more detailed LOD 350-400 (not LOD 300). Their commonly cited 14.7% figure covers total embodied GWP, but their production-stage-only (A1-A3) result shows a much larger gap: 0.308 kg CO2e/m^2/yr at LOD 200 versus 0.633 kg CO2e/m^2/yr at the detailed baseline, a 51.3% underestimation. Because their comparison spans a wider LOD range than this thesis's LOD 200-to-300 comparison, some of that larger gap likely comes from extra refinement between LOD 300 and LOD 400, a stage this thesis did not assess. This suggests the deviation found in this study may only capture part of the total deviation that would appear if extended to LOD 400.

6.5.2. COMPARISON WITH ELEMENT-LEVEL FINDINGS

A key contribution of this thesis is that it attributes deviation to specific building element categories and specific mechanisms (Sections 6.3 to 6.9). This level of detail is only partially matched by the reviewed literature.

Cavalliere et al. [67] offer the closest match to Research Question ii, since they organise their entire analysis around four construction categories: structure, envelope, interior, and technical equipment, and explicitly track each category's evolution across five design phases linked to LOD tiers. Their finding that exterior wall, underground, and ceiling show anomalous deviation, caused by finishing components being assumed present early and excluded later, directly answers the "which elements drive the greatest deviation" part of Research Question ii. This thesis extends this comparison further by identifying a parallel but reversed mechanism for windows and doors (Section 6.7), where frames were excluded early and included later, showing that inconsistent component inclusion across LOD stages is a recurring issue rather than one specific to either study.

Hollberg et al. [29] track individual elements (walls, slabs, ceilings, curtain walls, and others) in detail, down to single-element case examples. Still, since they do not use a formal LOD classification at all, their study cannot answer Research Question ii as posed, which specifically asks about comparison across Levels of Development. Their contribution instead lies in explaining the mechanisms behind element-level swings, such as placeholder materials and overlapping layers, which supports the "why deviation happens" discussion elsewhere in this thesis rather than a direct LOD-based comparison.

Rezaei et al. [74] did break down results by building assembly (foundation, exterior wall, floor and ceiling, roof, window, door, interior wall), closely matching this thesis's element classification. Their analysis identifies Foundation and Exterior Wall as the two largest contributors to environmental impact in the material production stage, a ranking that held consistently across both LOD 100 and LOD 300. They attribute the foundation's high impact to its concrete content, noting that early-stage designers have little ability to reduce this impact since accurate foundation quantities are typically finalised later by the structural team.

This approach, ranking assemblies by absolute impact rather than by deviation across LOD stages, is conceptually the same logic used to answer Research Question iii in this thesis: whether certain component groups can be considered negligible in BIM-based LCA due to their consistently minor contribution to total embodied carbon. Applying this logic to the results in Section 6.4, only Stairs can reasonably be considered negligible, contributing just 1.1% of total LOD 300 GWP Fossil, despite showing the largest percentage deviation of any category (-86.3%). External Walls, by contrast, contribute the largest share of total GWP in this study (36.5%) and cannot be considered negligible under any interpretation, a finding that echoes Rezaei et al.'s identification of exterior walls as one of the two dominant contributors in their own case study. The remaining four categories, Floor/Roof (27.9%), Internal Walls (13.9%), Windows/Doors (12.2%), and Foundation (8.4%), all contribute a meaningful share of total embodied carbon and likewise cannot be treated as negligible; notably, Foundation's smaller relative share in this thesis contrasts with Rezaei et al.'s finding of foundation as one of their top two contributors, which may partly reflect a methodological difference rather than a purely building-specific one. Rezaei et al.'s LOD 300 model was based on a real, fully specified project with actual structural design quantities. In contrast, the foundation quantities at each LOD stage in this thesis were derived from documented assumptions rather than a finalised structural design (Section 5.4.6.5). Since foundation and structural quantities are typically only confirmed late in the design process once the structural team finalises calculations, Foundation's contribution in this thesis may be underestimated relative to what a real, fully detailed project would show, suggesting the relative importance of specific assemblies may reflect both building-specific factors and the level of assumption-based versus real-project data underlying each study.

6.5.3. COMPARISON WITH PURPOSE-DRIVEN AND DATA-QUALITY PERSPECTIVES

Ferreira's Level of Information Need framework [44] highlights a source of deviation this thesis did not test: the switch from generic to manufacturer-specific EPDs (Environmental Product Declarations) as a design matures. Ferreira distinguishes an intermediate design stage that relies on generic, averaged EPD data (representing a typical material, not a real product) from a later stage that uses specific EPDs from an actual manufacturer. Their findings suggest that a meaningful share of early-stage deviation in BIM-LCA comes not just from changes in geometry or modelling detail, but from this underlying change in data quality.

This thesis used generic Ökobaudat EPDs at every LOD stage (Section 5.4.6.1) and never switched to manufacturer-specific data at LOD 300. This means the deviations measured in this thesis come only from changes in quantities, geometry, and component scope, not from any change in data source. As a result, the deviations reported here are likely smaller than what a real project would show, since a real project would typically also switch to specific EPDs at some point. That switch would add further variability on top of what this thesis captured. Testing this generic-to-specific EPD transition remains outside the scope of this thesis and represents a clear direction for future research.

6.5.4. WHOLE-BUILDING BENCHMARKING

To contextualise the magnitude of the embodied carbon results obtained in this study, the LOD 300 reference model was compared against external benchmark values published for the German building sector. This comparison serves a secondary, supporting function within the thesis: it does not validate the accuracy of the case study results, but rather offers an indication of whether the reported figures fall within a plausible order of magnitude relative to existing reference buildings.

The total embodied carbon results reported in Chapter 6 were originally normalised by the gross floor area (GFA) of the case study building, 274 m^2, covering the basement, ground floor, and first floor combined (Section 5.5). At the LOD 300 stage, this normalisation yields approximately 246.5 kg $CO2e/m^2GFA$ for GWP Fossil and 239.7 kg $CO2e/m^2GFA$ for GWP Total. However, the principal German benchmark available for this comparison, the DGNB System, reports its reference values per net room area (Nettoraumfläche, NSA) rather than gross floor area. Since NSA is a smaller and methodologically distinct area metric, defined as the usable floor area measured to the finished internal face of the walls bounding each room, a direct comparison using GFA would understate the building's true carbon intensity relative to DGNB's reference values. To address this, the building's Gross Internal Area (GIA) of 234 m^2, measured to the internal face of the external walls, was used as the closest available proxy for NSA, since GIA already excludes the external wall thickness that differentiates it from the GFA [90].

Re-normalising the LOD 300 results from the GFA basis to the GIA basis, using the ratio of the two known areas (274 m^2 divided by 234 m^2), produces an adjusted GWP Fossil value of approximately 288.7 kg $CO2e/m^2GIA$ and an adjusted GWP Total value of approximately 280.6 kg $CO2e/m^2GIA$. Annualising the GWP Fossil result over an assumed 50-year reference service life gives approximately 5.77 kg $CO2e/m^2GIA$ per year, which forms the basis for the comparison that follows.

DGNB's ENV1.1 criterion, indicator 2.5.1 ("CO2-reduziertes Bauwerk, Herstellungsphase"), evaluates the fossil greenhouse gas emissions (GWPfossil) of a building's production stage, Modules A1 to A3, against a defined reference value of 8.4 kg $CO2e/m^2NSA$ per year, with an upper target value of 3.75 kg $CO2e/m^2NSA$ per year required to achieve the Agenda 2030 bonus. This indicator corresponds directly to the system boundary and impact indicator assessed in this thesis [90]. A separate empirical study commissioned by DGNB, analysing fifty real certified buildings (forty-six office and four residential), found a measured mean of 7.3 kg $CO2e/m^2$ per year for the same Modules A1 to A3 scope, providing an additional, practice-based point of reference alongside DGNB's regulatory reference value [92].

Comparing the case study's annualised result of approximately 5.77 kg $CO2e/m^2$ per year against these reference points, the case study falls below both the DGNB regulatory reference value of 8.4 kg $CO2e/m^2NSA$ per year and the empirical mean of 7.3 kg $CO2e/m^2$ per year observed across the fifty certified buildings but remains above the more ambitious Agenda 2030 bonus threshold of 3.75 kg $CO2e/m^2NSA$ per year. Taken at face value, this would suggest that the case study building performs favourably relative to typical German construction practice. However, this conclusion must be qualified by the limitations discussed below.

A further, secondary point of reference is provided by the European Commission's Joint Research Centre (JRC) EFIResources report, which analysed seventy-two residential buildings under the earlier EN 15978:2011 standard, restricting its scope to the structural system only. This study reported embodied GWP values of approximately 5.5 to 9 kg $CO2e/m^2$ per year for multi-family residential buildings, a range that the case study's result of 5.77 kg $CO2e/m^2$ per year also falls within [93]. However, since this source

uses a different life cycle assessment standard and a narrower, structural-only system boundary than the present thesis, it cannot be treated as a precise, like-for-like benchmark. It is used here only as a rough plausibility check, confirming that the case study's result sits within a broadly similar range to comparable buildings, rather than as formal validation against a matching standard.

Several limitations reduce how much confidence we can place in this benchmarking comparison. These limitations suggest that the case study's result is probably closer to the DGNB reference values than it first appears, not that the building genuinely performs better than typical German buildings. First, GIA was used as an approximation for NSA rather than as a direct measurement of it. GIA still includes the footprint of internal partition walls, which true NSA excludes, meaning the building's actual NSA is somewhat smaller than the 234 m^2 figure used, and the true NSA-normalised carbon intensity would consequently be somewhat higher than the 5.77 kg CO2e/m^2 per year reported here. Second, steel reinforcement was excluded from all concrete elements, including foundations, slabs, beams, and columns, throughout the LOD 300 model. This exclusion is consistent with the BIMForum LOD Specification, which explicitly assigns reinforcement detailing to LOD 400 rather than LOD 300, and therefore reflects a specification-compliant boundary of the modelling stage rather than an error. Nevertheless, reinforcement steel has been shown in the literature to contribute approximately 20 to 35% of total structural embodied carbon in reinforced concrete elements, depending on member type and reinforcement ratio [94]. Third, flooring finish materials, including ceramic tile, were not modelled at any LOD stage within this thesis, representing a further, unquantified source of underestimation in the reported results.

Taken together, correcting for the GIA-to-NSA gap and reintroducing the excluded reinforcement and flooring finish scope would likely raise the case study's true embodied carbon intensity meaningfully above the 5.77 kg CO2e/m^2 per year figure reported here, potentially bringing it closer to, or even above, the DGNB reference value of 8.4 kg CO2e/m^2NSA per year, rather than comfortably below it as the uncorrected comparison suggests. This benchmarking comparison should therefore be interpreted as a rough, favourable-but-uncertain indication that the case study's results fall within a plausible order of magnitude, rather than as validated confirmation that the building outperforms typical German reference buildings. Accordingly, it is presented here as a secondary, supporting comparison, and the primary evidence addressing Research Question iv is drawn from the direct comparison with existing BIM-LCA literature presented in Chapter 4.

6.6. Limitations

The findings presented in this chapter should be interpreted in light of several methodological limitations, many of which were anticipated in the validity and limitations discussion of Chapter 5 but can now be evaluated more concretely against the actual results obtained.

6.6.1. LOD 100 ASSUMPTION-HEAVY TAKEOFF

The results in Section 6.3 confirm that LOD 100 deviations are highly variable in both direction and magnitude across element categories, ranging from +59.3% for internal walls to -59.6% for floor and roof elements, rather than following a single consistent bias. This variability directly reflects the assumption-based nature of the LOD 100 quantity takeoff described in Section 5.4.6.5, where shape factor geometry estimates and default ratios sourced from One Click LCA's Carbon Designer tool

substitute for actual modelled geometry, meaning any single LOD 100 result should be treated as indicative rather than precise. The whole-building deviation reported in Section 6.2 should not be interpreted as evidence that LOD 100 assumptions are broadly reliable, since offsetting errors across categories can mask substantial element-level inaccuracy. A further limitation specific to the Stairs category should be noted separately: since no reliable assumption-based method could be identified for estimating stair quantities at LOD 100, the LOD 200 concrete volume was carried over as a direct proxy for this category. Consequently, the LOD 100 result for Stairs (Section 6.3.5), which shows a deviation of -86.3%, does not reflect an independent estimation methodology and should not be treated as comparable in analytical value to the LOD 100 results derived for other categories. Where this chapter reports an overall element-level deviation range inclusive of Stairs, it therefore spans -86.3% to +59.3%, whereas the range excluding this special case spans +59.3% to -59.6%; these two framings are not contradictory but reflect whether the non-independent Stairs proxy is included.

6.6.2. SIMPLIFIED GEOMETRY BETWEEN LOD 200 AND LOD 300

As anticipated in Section 5.6.3, stairs, windows, and doors were modelled using the same predefined Revit family geometry at both LOD 200 and LOD 300, meaning no true geometric refinement occurred for these elements between stages. For windows and doors, the substantial deviation observed (Section 6.3.5) instead originated from a deliberate LCA material mapping decision, made in accordance with BIM Forum's specification that only a generic object is required at LOD 200 for these elements. In contrast, frame and panel detail is required at LOD 300, rather than from any visible change in modelled geometry. While this approach is consistent with the intended LOD specification, it means the deviation reported for this category reflects a mapping-stage implementation of LOD progression rather than a geometry-driven one, and this distinction should be kept in mind when comparing this category's deviation mechanism to others in this chapter. Similarly, for Stairs, the LOD 200 to LOD 300 increase was driven specifically by the addition of a steel railing, a new, higher-carbon material absent from the LOD 200 material scope, rather than by any refinement of the existing concrete-based riser, tread, or stringer geometry.

6.6.3. EXCLUDED REINFORCEMENT AND FINISH LAYERS

Consistent with the BIMForum LOD Specification, steel reinforcement was excluded from all concrete elements, including foundations, slabs, beams, and columns, throughout every LOD stage assessed in this chapter, since reinforcement detailing (including hooks, lap splices, and shear reinforcement) is explicitly defined as an LOD 400 requirement, not LOD 300. Flooring finish materials, including ceramic tile, were similarly not modelled at any LOD stage in this thesis. Both omissions apply uniformly across LOD 100, LOD 200, and LOD 300, meaning they do not distort the relative LOD-to-LOD deviation comparisons central to Research Questions i to ii, since the same exclusions are held constant across all three models. However, they do mean that all absolute GWP figures reported in this chapter, including the whole-building benchmarking comparison in Section 6.5, likely understate the building's true embodied carbon relative to what a fully detailed LOD 400 model would report, and this should be kept in mind whenever an absolute figure from this chapter is compared against an external reference value.

6.6.4. MANUAL MAPPING SUBJECTIVITY

The manual, element-by-element material mapping process described in Section 5.4.6.2, along with specific adjustments such as the metal stud quantity estimation, the roof rafter coverage correction, and the door and window frame inclusion decisions (Section 5.4.6.3), introduces a degree of subjectivity that cannot be fully separated from the LOD-driven deviations reported in this chapter. Some portion of the deviation observed, particularly for the windows and doors, internal walls, and floor/roof categories, may therefore reflect specific mapping and correction decisions made in this study rather than an inherent, generalizable property of LOD progression itself.

6.6.5. SINGLE CASE STUDY BUILDING

As established in Section 5.6.2, all results in this chapter pertain to a single, relatively simple case study building, and the specific percentage deviations reported here should not be generalised as fixed benchmark values applicable to other projects. The relatively small proportion of geometric change introduced between LOD 200 and LOD 300 for this building's structural shell (Section 5.6.3) likely means that the deviations reported here represent a conservative estimate, and a more architecturally complex real-world project would plausibly exhibit larger deviations between these stages.

6.6.6. A1-A3 SYSTEM BOUNDARY

All results are restricted to the production stage (modules A1-A3), consistent with Section 5.4.5, meaning the findings in this chapter address only the embodied carbon associated with material production and do not capture end-of-life, replacement, or operational carbon impacts. The comparative conclusions drawn here should therefore be understood as specific to upfront embodied carbon rather than whole-life carbon performance.

6.6.7. BENCHMARKING COMPARABILITY

The external literature and DGNB benchmarking conducted in Section 6.5, which addresses Research Question iv, is limited by several factors that affect the precision of the comparison. First, the studies reviewed vary in system boundary, building typology, and treatment of GWP Fossil versus GWP Total, meaning cross-study comparisons cannot be treated as fully equivalent. Second, the DGNB comparison specifically required approximating the net room area (NSA) using the building's Gross Internal Area (GIA) of 234 m^2, since a true NSA figure was not directly available from the model; because GIA still includes internal partition wall footprints that true NSA excludes, this proxy likely understates the true NSA-normalised carbon intensity, meaning the case study may appear more favourable against DGNB reference values than a precise NSA-based calculation would show. Taken together with the excluded reinforcement and flooring finish layers noted above, these factors mean the whole-building benchmarking comparison should be read as a plausibility check on the order of magnitude of the results, and the findings addressing Research Question iv should be treated as indicative rather than conclusive.

6.7. IMPLICATIONS FOR PRACTICE

The findings of this chapter carry several practical implications for how BIM-based LCA is conducted at early design stages, particularly for practitioners relying on lower-LOD models to estimate embodied carbon before detailed design information becomes available.

6.7.1. WHOLE-BUILDING ESTIMATES CAN MASK ELEMENT-LEVEL ERROR

The whole-building comparison in Section 6.2 showed a relatively modest deviation for LOD 100 (-5.1% for GWP Fossil) compared to LOD 200 (-9.0% for GWP Fossil), yet the element-level analysis in Sections 6.3 to 6.8 revealed that this apparent accuracy resulted from large, offsetting errors across categories, ranging from -86.3% to +59.3%, rather than genuine precision. This is an important caution for practitioners: a plausible-looking whole-building GWP estimate at LOD 100 does not guarantee that any individual element category, or any design decision made based on that category, is reliably estimated, and element-level results should not be trusted at LOD 100 even when the aggregate figure appears reasonable.

6.7.2. TIMBER ELEMENTS REQUIRE DUAL-INDICATOR REPORTING

The pronounced Fossil-Total divergence identified for the Floor/Roof category in Section 6.5, where GWP Fossil and GWP Total moved in opposite directions at LOD 200 due to the timber rafter coverage correction, and the smaller but consistent divergence identified for the Windows/Doors category due to the wooden door panels (Section 6.3.6), together demonstrate that practitioners working with timber-inclusive assemblies should report both GWP Fossil and GWP Total rather than relying on a single indicator, since the choice of indicator alone can change the conclusion about whether a model overestimates or underestimates embodied carbon for that element. This has direct relevance for DGNB-certified projects, where GWP Fossil is the specific metric assessed under criterion ENV1.1, indicator 2.5.1, since teams should be aware that a favourable GWP Fossil result for a timber-inclusive element may not correspond to an equally favourable GWP Total picture, and vice versa.

6.7.3. DISCRETE STRUCTURAL SYSTEMS ARE PRONE TO OVERESTIMATION

The roof rafter and metal stud partition corrections applied in this study (Sections 6.3.3 and 6.3.4) show that spacing- or interval-based structural systems, where discrete members are separated by voids or infill material, are particularly prone to overestimation if quantity takeoffs treat a modelled layer as a continuous solid material rather than accounting for actual member spacing. Practitioners relying on default BIM layer quantities for timber or metal stud assemblies without applying a coverage or spacing correction risk substantially overestimating both material quantity and embodied carbon for these elements.

6.7.4. WINDOWS AND DOORS WARRANT EARLY, SPECIFICATION-CONSISTENT MAPPING

Contrary to a common assumption that envelope openings are a minor contributor to embodied carbon, the windows and doors category showed some of the largest and most persistent deviations across LOD stages (Section 6.7), driven by a material-mapping scope decision aligned with BIM Forum's LOD

specification rather than by geometric imprecision alone. Practitioners should ensure that door and window frame components are captured consistently with the intended LOD specification at each modelling stage, since deferring this detail to a later LOD stage, as occurred in this study, can produce a large jump in reported GWP even when the underlying model geometry has not changed.

6.7.5. STRUCTURAL ENVELOPE DOMINATES, BUT FOUNDATION GWP IMPACT IS LOW

Consistent with the wider literature reviewed in Section 6.10, the external wall and façade category represented the largest single share of total embodied carbon in this study (36.5% of GWP Fossil), confirming that structural envelope decisions should remain the primary focus of early-stage carbon reduction strategies. However, the foundation category share of embodied carbon was lower than expected. The reason behind this is probably that the steel is not included in the concrete.

6.7.6. NEGLIGIBILITY SHOULD BE ASSESSED BY CONTRIBUTION SHARE, NOT BY DEVIATION

The stairs category, despite showing the largest relative deviation of any category (-86.3%), contributes only 1.1% of total LOD 300 GWP and can reasonably be treated as negligible on that basis. This confirms that negligibility, as posed in Research Question iii, should be assessed strictly by a category's absolute share of total embodied carbon rather than by the magnitude of its deviation across LOD stages, since these two properties are independent of one another: a category can be highly volatile without being significant, and a category can be significant without being volatile, as seen with External Walls. Practitioners deciding which element categories can reasonably be deprioritised in an early-stage LCA should base that decision on absolute GWP share alone, while treating high deviation as a separate signal indicating where additional modelling caution or early-stage sensitivity analysis may be warranted.

7
CONCLUSION

7.1. SUMMARY OF FINDINGS

This thesis set out to investigate how the Level of Development (LOD) of a BIM model influences the results of a building-based life cycle assessment, using a single case study building assessed at LOD 100, LOD 200, and LOD 300 under the BIMForum LOD Specification and the EN 15804+A2 standard via One Click LCA. Four research questions guided this investigation, and the findings can be summarised against each in turn.

Research Question i asked how large the deviation in embodied carbon is between LOD 100/200 and LOD 300. The results showed that this deviation is not simply progressive or one-directional: total building GWP Fossil moved from **64,064 kg CO_2e** at LOD 100, down to **61,464 kg CO_2e** at LOD 200 (a −9.0% deviation), before rising to **67,532 kg CO_2e** at LOD 300.This non-monotonic pattern is itself an important finding, since it contradicts a simple assumption that lower-LOD models consistently overestimate or consistently underestimate embodied carbon relative to higher-LOD models.

Research Question ii asked which building elements drive the greatest share of this deviation. The element-level analysis revealed that aggregated, whole-building comparisons mask substantial offsetting errors at the element level. Individual element categories showed deviations ranging from -86.3% (stairs), -59.7% (Windows/Doors), and -29% (floor and roof elements) at LOD 200. Two distinct mechanisms explained most of this variation: geometric refinement, where discrete structural members (timber rafters, metal studs) were incorrectly treated as continuous solid layers at lower LOD stages, and material scope expansion, where components such as window and door frames were absent from lower-LOD material mapping and only introduced at LOD 300, consistent with the BIMForum specification's staged inclusions.

Research Question iii asked whether certain component groups could be considered negligible in BIM-based LCA. The findings show that negligibility must be assessed by a category's absolute contribution share, not by the magnitude of its deviation across LOD stages. The Stairs category, despite showing the largest relative deviation observed in this study, contributed only 1.1% of total LOD 300 GWP and can reasonably be treated as negligible on that basis. In contrast, the External Walls and Façade category represents the largest absolute contribution, similar to previous studies mentioned in the state of the art.

Research Question iv asked how these findings compare with existing BIM-LCA research. As discussed in Section 6.5, the comparison revealed that early-stage deviation direction and magnitude vary considerably across studies depending on the underlying modelling philosophy: Cavalliere et al. [67], and Rezaei et al. [74], relied on catalogue-based assemblies and probabilistic simulation, respectively,

while Hollberg et al. [29] tracked an evolving real building without a formal LOD framework at al. This thesis's deterministic, specification-driven approach, applying the BIMForum LOD Specification directly through documented, geometry-linked assumptions rather than averaged data or simulated ranges, distinguishes it from all three, and helps explain why its whole-building deviation was comparatively modest even as substantial, offsetting element-level volatility emerged beneath that aggregate figure.

7.2. CONTRIBUTION OF THE STUDY

This thesis contributes a structured, specification-anchored method for assessing LOD-driven variability in embodied carbon results, grounded explicitly in the BIMForum LOD Specification rather than informal or inconsistent LOD interpretations sometimes seen in prior BIM-LCA literature. By applying consistent structural material assumptions across all three LOD stages and isolating LOD as the primary variable under investigation, the study demonstrates a transferable method for evaluating how modelling detail affects LCA outcomes, independent of the specific case study building's own numerical results. The identification of two distinct, generalizable mechanisms, geometric refinement and material scope expansion, as explanations for LOD-driven deviation offers a conceptual framework that future BIM-LCA studies can apply to other buildings, element types, or LCA tools.

7.3. LIMITATIONS

As discussed in detail in Section 6.11, this study's findings are subject to several limitations that should be considered when interpreting its conclusions. The results derive from a single, relatively simple case study building and cannot be generalised as fixed benchmark values applicable to other projects, typologies, or LCA platforms. The LOD 100 quantity takeoff relied heavily on assumption-based shape factors and default ratios rather than modelled geometry, meaning its results carry inherently higher uncertainty than the LOD 200 and LOD 300 results.

Given the scale of assumption embedded in this stage, this thesis's findings support a stronger conclusion than uncertainty alone: LOD 100 may not constitute a genuinely useful basis for embodied carbon assessment at all, since its quantities are derived from generic default ratios rather than any project-specific information, meaning any resulting GWP figure reflects the assumption set applied rather than the building being assessed.

Steel reinforcement was excluded from all concrete elements consistent with the BIMForum specification's assignment of reinforcement to LOD 400, and flooring finish materials were not modelled at any stage, meaning all absolute GWP figures reported in this thesis likely understate the building's true embodied carbon. Finally, the system boundary was restricted to the production stage (Modules A1-A3) throughout, meaning the study addresses upfront embodied carbon only, not whole-life carbon performance.

7.4. RECOMMENDATIONS FOR PRACTICE

Building on the implications discussed in Section 6.7, this study suggests several practical recommendations for professionals conducting BIM-based LCA at early design stages. Practitioners should not treat a plausible-looking whole-building GWP estimate at low LOD as evidence that individual

element categories are reliably estimated, since offsetting errors can mask substantial element-level inaccuracy. For assemblies involving discrete structural members, such as timber rafters or metal stud framing, practitioners should apply a coverage or spacing correction rather than treating a modelled layer as a continuous solid material, to avoid substantial overestimation. For timber-inclusive assemblies, both GWP Fossil and GWP Total should be reported, since the two indicators can diverge and even move in opposite directions across LOD stages. Decisions about which element categories can reasonably be deprioritised in an early-stage assessment should be based on a category's absolute contribution to total embodied carbon, not on its volatility across LOD stages.

Given the divergence observed between GWP Fossil and GWP Total across LOD stages in this study, this thesis also highlights a broader need for the BIM-LCA field to adopt a single, universally reported GWP indicator, or at minimum a mandatory dual-reporting convention, since studies and certification schemes that report only one indicator risk drawing opposite conclusions about the same building depending on which metric is used.

7.5. RECOMMENDATIONS FOR FUTURE RESEARCH

Several avenues for future research emerge from this study. First, this method should be applied to a more architecturally complex building, since the relatively simple geometry of the building assessed here likely produced conservative estimates of LOD-driven deviation, particularly between LOD 200 and LOD 300. Second, future studies could extend the system boundary beyond Modules A1-A3 to include replacement (B4) and end-of-life (C3-C4) impacts, enabling a fuller whole-life carbon comparison across LOD stages. Third, incorporating steel reinforcement and finish layer materials, appropriately modelled at LOD 400 or through supplementary quantity estimation methods, would allow a more complete accounting of embodied carbon and a more precise comparison against certification benchmarks such as DGNB's reference values. Moreover, future research could explore whether the two mechanisms identified in this study, geometric refinement and material scope expansion, generalise consistently across different building typologies, structural systems, and LCA software platforms, which would strengthen the broader applicability of the findings presented here.

Finally, this thesis suggests that the BIMForum LOD Specification, though useful as a geometry and detail-focused framework, may be insufficient on its own to guide BIM-based LCA practice, since it defines what geometric and material information should exist at each stage without specifying what information is actually needed to support a reliable carbon calculation. Future research could explore whether a complementary framework, such as the Level of Information Need (LOIN) concept introduced under EN 17412-1:2020 (now superseded by ISO 7817-1:2024), could be adapted alongside LOD to define carbon-assessment-specific information requirements at each project stage, potentially closing the gap between geometric development and LCA data readiness identified in this study.

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9
ANNEXES

A. 1 Bill of Materials LOD 100

CLASS	MATERIAL	QUANTITY	QTY_TYPE	THICKNESS_MM
DOOR	Wooden doors, calculated average for Germany, 1.23x2.18 m, 36 kg/m2, 96 kg/unit (One Click LCA)	10.6	m2	
SLAB	Ready-mix concrete C25/30, C25/30, 2300 kg/m3, EN15804+A2, ref. year 2023	170	m2	200
ROOF	Solid construction timber (15% moisture / 13% H2O content), 529 kg/m3, 15% moisture content, EN15804+A2, ref. year 2023	0.3	m3	
WINDOW	Insulated glazing, triple pane, 30 kg/m2, EN15804+A2, ref. year 2023	66.6	m2	
FOUNDATION	Ready-mix concrete C25/30, C25/30, 2300 kg/m3, EN15804+A2, ref. year 2023	18.26	m3	300
EXTERNAL WALL	Ready-mix concrete C25/30, C25/30, 2300 kg/m3, EN15804+A2, ref. year 2023	111	m2	350
OTHER	Ready-mix concrete C25/30, C25/30, 2300 kg/m3, EN15804+A2, ref. year 2023	0.449	m3	200
EXTERNAL WALL	Sand-lime brick, 2000 kg/m3, EN15804+A2, ref. year 2023	77.7	m3	
INTERNAL WALL	Sand-lime brick, 2000 kg/m3, EN15804+A2, ref. year 2023	47.95	m3	

A. 2 Bill of Materials LOD 200

CLASS	MATERIAL	QUANTITY	QTY_TYPE	THICKNESS_MM
ROOF	Solid construction timber (15% moisture / 13% H2O content), 529 kg/m3, 15% moisture content, EN15804+A2, ref. year 2023	9.12	m3	
FOUNDATION	Ready-mix concrete C25/30, C25/30, 2300 kg/m3, EN15804+A2, ref. year 2023	27.41	m3	
SLAB	Ready-mix concrete C25/30, C25/30, 2300 kg/m3, EN15804+A2, ref. year 2023	32.048	m3	168.31
WINDOW	Insulated glazing, triple pane, 30 kg/m2, EN15804+A2, ref. year 2023	40.34	m2	
DOOR	Wooden doors, calculated average for Germany, 1.23x2.18 m, 36 kg/m2, 96 kg/unit (One Click LCA)	21.81	m2	
BEAM	Dry floor screed, gypsum fiber board, 25 mm, 24.07 kg/m2, 960 kg/m3, EN15804+A2, ref. year 2023	234.59	m2	60
EXTERNAL WALL	Ready-mix concrete C25/30, C25/30, 2300 kg/m3, EN15804+A2, ref. year 2023	92.4	m2	370
OTHER	Ready-mix concrete C25/30, C25/30, 2300 kg/m3, EN15804+A2, ref. year 2023	0.45	m3	200
EXTERNAL WALL	Gypsum interior plaster, 900 kg/m3, EN15804+A2, ref. year 2023	2.537	m3	
EXTERNAL WALL	Mineral wool (facade insulation), 46.25 kg/m3, EN15804+A2, ref. year 2023	16.91	m3	
EXTERNAL WALL	Lime paint, 0.15-0.25 kg/m2, 1700-1900 kg/m3, EN15804+A2, ref. year 2021	2.53	m3	
EXTERNAL WALL	Sand-lime brick, 2000 kg/m3, EN15804+A2, ref. year 2023	29.598	m3	
BEAM	Extruded polystyrene (XPS), 32 kg/m3, EN15804+A2, ref. year 2023	5.948	m3	

INTERNAL WALL	Sand-lime brick, 2000 kg/m3, EN15804+A2, ref. year 2023	22.844	m3	
INTERNAL WALL	Galvanized steel stud framing profiles per m2 (air gap included), UD and CD profiles included, wing width: 6 mm, flange width:50 mm, steel thicnkess:0.6 mm (23 gauge), 450 mm spacing, 2.4 kg/m2 (One Click LCA)	442	kg	
BEAM	Roof tile, 45 kg/m2, EN15804+A2, ref. year 2021	114.08	m2	
BEAM	Mineral wool (facade insulation), 46.25 kg/m3, EN15804+A2, ref. year 2023	18.25	m3	
BEAM	Gypsum wallboard, 100 mm, 84 kg/m2, 840 kg/m3, EN15804+A2, ref. year 2023	114.08	m2	100
BEAM	Gypsum fiber board, 25 mm, 24.07 kg/m2, 960 kg/m3, EN15804+A2, ref. year 2022	114.08	m2	25

A. 3 Bill of Materials LOD 300

CLASS	MATERIAL	QUANTITY	QTY_TYPE	THICKNESS_MM
ROOF	Roof tile, 45 kg/m2, EN15804+A2, ref. year 2021	114.08	m2	
ROOF	Solid construction timber (15% moisture / 13% H2O content), 529 kg/m3, 15% moisture content, EN15804+A2, ref. year 2023	0.71	m3	
FOUNDATION	Ready-mix concrete C25/30, C25/30, 2300 kg/m3, EN15804+A2, ref. year 2023	18.18	m3	
SLAB	Ready-mix concrete C25/30, C25/30, 2300 kg/m3, EN15804+A2, ref. year 2023	32.048	m3	168.31
DOOR	Wooden doors, calculated average for Germany, 1.23x2.18 m, 36 kg/m2, 96 kg/unit (One Click LCA)	21.81	m2	
BEAM	Dry floor screed, gypsum fiber board, 25 mm, 24.07 kg/m2, 960 kg/m3, EN15804+A2, ref. year 2023	234.59	m2	60

EXTERNAL WALL	Ready-mix concrete C25/30, C25/30, 2300 kg/m3, EN15804+A2, ref. year 2023	108.66	m2	280
OTHER	Ready-mix concrete C25/30, C25/30, 2300 kg/m3, EN15804+A2, ref. year 2023	0.47	m3	200
EXTERNAL WALL	Damp insulation PE, 0.2 kg/m2, EN15804+A2, ref. year 2023	108.66	m2	
EXTERNAL WALL	Gypsum interior plaster, 900 kg/m3, EN15804+A2, ref. year 2023	2.537	m3	
EXTERNAL WALL	Mineral wool (facade insulation), 46.25 kg/m3, EN15804+A2, ref. year 2023	27.061	m3	
EXTERNAL WALL	Lime paint, 0.15-0.25 kg/m2, 1700-1900 kg/m3, EN15804+A2, ref. year 2021	3.383	m3	
EXTERNAL WALL	Sand-lime brick, 2000 kg/m3, EN15804+A2, ref. year 2023	29.598	m3	
EXTERNAL WALL	Extruded polystyrene (XPS), 32 kg/m3, EN15804+A2, ref. year 2023	8.87	m3	
BEAM	Mineral wool (facade insulation), 46.25 kg/m3, EN15804+A2, ref. year 2023	18.252	m3	
BEAM	Gypsum wallboard, 100 mm, 84 kg/m2, 840 kg/m3, EN15804+A2, ref. year 2023	114.08	m2	100
BEAM	Gypsum fiber board, 25 mm, 24.07 kg/m2, 960 kg/m3, EN15804+A2, ref. year 2022	114.08	m2	25
BEAM	Extruded polystyrene (XPS), 32 kg/m3, EN15804+A2, ref. year 2023	5.948	m3	
INTERNAL WALL	Gypsum interior plaster, 900 kg/m3, EN15804+A2, ref. year 2023	3.44	m3	

INTERNAL WALL	Sand-lime brick, 2000 kg/m3, EN15804+A2, ref. year 2023	22.844	m3	
INTERNAL WALL	Galvanized steel stud framing profiles per m2 (air gap included), UD and CD profiles included, wing width: 6 mm, flange width:50 mm, steel thicnkess:0.6 mm (23 gauge), 450 mm spacing, 2.4 kg/m2 (One Click LCA)	531	kg	
FOUNDATION	Ready-mix concrete C25/30, C25/30, 2300 kg/m3, EN15804+A2, ref. year 2023	7.435	m3	
INTERNAL WALL	Gypsum plaster board, fire resistant, 12.5 mm, 10 kg/m2, EN15804+A2, ref. year 2023	53.805	m2	12.5
DOOR	Aluminium frame window triple glazed, operable(tilt and turn), 0% recycled aluminium, 1.48 m x 2.18 m, 32.6 kg/m2 (One Click LCA)	40.34	m2	
DOOR	Medium density fibreboard (MDF), 700 kg/m3 (KRONOSPAN GmbH)	0.471	m3	
OTHER	Railing and fencing, calculated average for Germany, 40 kg/m (One Click LCA)	6.79	m	

A. 4 Life-Cycle Assessment Results A1-A3 for LOD 100

Project users	**Project name**	**Design name**	**Date**	**Tool name**				
Nahom Kiflemariam Abraham	Project Thesis	LOD 100	7/15/26	Level(s) life-cycle assessment (EN15804+A2)				
Section	**Resource**	**User input**	**Unit**	**Global Warming Potential total, kg CO2e**	**Global Warming Potential fossil, kg CO2e**	**Global Warming Potential biogenic, kg CO2e**	**Global Warming Potential, LULUC, kg CO2e**	**Question**

A1-A3	Ready-mix concrete C25/30, C25/30, 2300 kg/m3, EN15804+A2, ref. year 2023	21.25	m3	4047.45	4049.2	-6.37	4.63	Foundation, sub-surface, basement and retaining walls
A1-A3	Ready-mix concrete C25/30, C25/30, 2300 kg/m3, EN15804+A2, ref. year 2023	92.5	m2	8611.37	8615.08	-13.55	9.84	External walls and facade
A1-A3	Sand-lime brick, 2000 kg/m3, EN15804+A2, ref. year 2023	74.76	m3	24218.97	24186.4	11.15	21.41	External walls and facade
A1-A3	Sum			32830.34	32801.48	-2.4		External walls and facade
A1-A3	Ready-mix concrete C25/30, C25/30, 2300 kg/m3, EN15804+A2, ref. year 2023	170	m2	7536.33	7539.58	-11.86	8.61	Floor slabs, ceilings, roofing decks, beams and roof
A1-A3	Solid construction timber (15% moisture / 13% H2O content), 529 kg/m3, 15% moisture content, EN15804+A2, ref. year 2023	17	m3	-188.81	64.56	-253.76	0.389	Floor slabs, ceilings, roofing decks, beams and roof
A1-A3	Sum			7347.52	7604.14	-265.62	8.999	Floor slabs, ceilings, roofing decks, beams and roof
A1-A3	Sand-lime brick, 2000 kg/m3, EN15804+A2, ref. year 2023	47.95	m3	14945.94	14925.84	6.88	13.21	Internal walls and non-bearing structures
A1-A3	Ready-mix concrete C25/30, C25/30, 2300 kg/m3, EN15804+A2, ref. year 2023	0.449	m3	99.52	99.57	-0.157	0.114	Other structures and materials
A1-A3	Wooden doors, calculated average for Germany, 1.23x2.18 m, 36 kg/m2, 96 kg/unit, One Click LCA	10.6	m2	186.14	616.39	-442.44	12.19	Windows and doors

A1-A3	Insulated glazing, triple pane, 30 kg/m2, EN15804+A2, ref. year 2023	66.6	m 2	3980.34	3966.94	8.39	5	Windows and doors
A1-A3	Sum			4166.48	4583.33	-434.05	17.19	Windows and doors
A1-A3	Total Sum			63437.25	64063.56	-701.717	44.143	

A. 5 Life-Cycle Assessment Results A1-A3 for LOD 200

Project users	**Project name**	**Design name**	**Date**	**Tool name**				
Nahom Kiflemariam Abraham	Project Thesis	LOD 200	7/15/26	Level(s) life-cycle assessment (EN15804 +A2)				
Section	**Resource**	**User input**	**Unit**	**Global Warming Potential total, kg CO2e**	**Global Warming Potential fossil, kg CO2e**	**Global Warming Potential biogenic, kg CO2e**	**Global Warming Potential, LULUC, kg CO2e**	**Question**
A1-A3	Ready-mix concrete C25/30, C25/30, 2300 kg/m3, EN15804+A2, ref. year 2023	27.41	m 3	6075.61	6078.23	-9.56	6.94	Foundation, sub-surface, basement and retaining walls
A1-A3	Ready-mix concrete C25/30, C25/30, 2300 kg/m3, EN15804+A2, ref. year 2023	92.4	m 2	7578	7581.27	-11.93	8.66	External walls and facade
A1-A3	Gypsum interior plaster, 900 kg/m3, EN15804+A2, ref. year 2023	2.537	m 3	308.43	311.29	-2.98	0.12	External walls and facade

A1-A3	Mineral wool (facade insulation), 46.25 kg/m3, EN15804+A2, ref. year 2023	16.91	m3	1132.55	1123.6	8.32	0.627	External walls and facade
A1-A3	Lime paint, 0.15-0.25 kg/m2, 1700-1900 kg/m3, EN15804+A2, ref. year 2021	2.53	m3	4244.81	4224.55	18.73	1.53	External walls and facade
A1-A3	Sand-lime brick, 2000 kg/m3, EN15804+A2, ref. year 2023	29.598	m3	9225.65	9213.24	4.25	8.16	External walls and facade
A1-A3	**Sum**			22489.44	22453.95	16.39	19.097	External walls and facade
A1-A3	Solid construction timber (15% moisture / 13% H2O content), 529 kg/m3, 15% moisture content, EN15804+A2, ref. year 2023	9.12	m3	-5739.86	1962.63	-7714.32	11.84	Floor slabs, ceilings, roofing decks, beams and roof
A1-A3	Ready-mix concrete C25/30, C25/30, 2300 kg/m3, EN15804+A2, ref. year 2023	32.048	m3	7103.66	7106.72	-11.18	8.12	Floor slabs, ceilings, roofing decks, beams and roof
A1-A3	Dry floor screed, gypsum fiber board, 25 mm, 24.07 kg/m2, 960 kg/m3, EN15804+A2, ref. year 2023	234.59	m2	4405.49	4391.07	11.9	2.52	Floor slabs, ceilings, roofing decks, beams and roof
A1-A3	Extruded polystyrene (XPS), 32 kg/m3, EN15804+A2, ref. year 2023	5.948	m3	606.81	604.08	2.56	0.174	Floor slabs, ceilings, roofing decks, beams and roof
A1-A3	Roof tile, 45 kg/m2, EN15804+A2, ref. year 2021	114.08	m2	1836.68	1828.03	7.37	1.29	Floor slabs, ceilings, roofing decks, beams and roof
A1-A3	Mineral wool (facade insulation), 46.25 kg/m3, EN15804+A2, ref. year 2023	18.25	m3	1222.29	1212.63	8.98	0.676	Floor slabs, ceilings, roofing decks, beams and roof

A1-A3	Gypsum wallboard, 100 mm, 84 kg/m2, 840 kg/m3, EN15804+A2, ref. year 2023	114.08	m2	2691.25	2685.24	4.38	1.62	Floor slabs, ceilings, roofing decks, beams and roof
A1-A3	Gypsum fiber board, 25 mm, 24.07 kg/m2, 960 kg/m3, EN15804+A2, ref. year 2022	114.08	m2	837.8	834.12	3.5	0.181	Floor slabs, ceilings, roofing decks, beams and roof
A1-A3	**Sum**			12964.12	20624.52	-7686.81	26.421	Floor slabs, ceilings, roofing decks, beams and roof
A1-A3	Sand-lime brick, 2000 kg/m3, EN15804+A2, ref. year 2023	25.45	m3	7120.44	7110.86	3.28	6.29	Internal walls and non-bearing structures
A1-A3	Galvanized steel stud, 500 mm centre, 6.5 kg/m, One Click LCA	516.4	kg	1434.52	1425.45	7.24	1.83	Internal walls and non-bearing structures
A1-A3	**Sum**			8554.96	8536.31	10.52	8.12	Internal walls and non-bearing structures
A1-A3	Ready-mix concrete C25/30, C25/30, 2300 kg/m3, EN15804+A2, ref. year 2023	0.449	m3	99.75	99.79	-0.157	0.114	Other structures and materials
A1-A3	Wooden doors, calculated average for Germany, 1.23x2.18 m, 36 kg/m2, 96 kg/unit, One Click LCA	21.81	m2	2410.92	2402.8	5.08	3.03	Windows and doors
A1-A3	Insulated glazing, triple pane, 30 kg/m2, EN15804+A2, ref. year 2023	40.34	m2	382.98	1268.25	-910.35	25.08	Windows and doors
A1-A3	**Sum**			2793.9	3671.05	-905.27	28.11	
Subtotal for A1-A3:				**52977.78**	**61463.85**	**-8574.887**	**88.802**	

A. 6 Life-Cycle Assessment Results A1-A3 for LOD 300

Project users	**Project name**	**Design name**	**Date**	**Tool name**				
Nahom Kiflemariam Abraham	Project Thesis	**LOD 300**	7/15/26	Level(s) life-cycle assessment (EN15804 +A2)				
Section	**Resource**	**User input**	**Unit**	**Global Warming Potential total, kg CO2e**	**Global Warming Potential fossil, kg CO2e**	**Global Warming Potential biogenic, kg CO2e**	**Global Warming Potential, LULUC, kg CO2e**	**Question**
A1-A3	Ready-mix concrete C25/30, C25/30, 2300 kg/m3, EN15804+A2, ref. year 2023	18.18	m3	4029.72	4031.46	-6.34	4.61	Foundation, sub-surface, basement and retaining walls
A1-A3	Ready-mix concrete C25/30, C25/30, 2300 kg/m3, EN15804+A2, ref. year 2023	7.435	m3	1648.02	1648.73	-2.59	1.88	Foundation, sub-surface, basement and retaining walls
A1-A3	Sum			5677.74	5680.19	-8.93	6.49	Foundation, sub-surface, basement and retaining walls

A1-A3	Ready-mix concrete C25/30, C25/30, 2300 kg/m3, EN15804+A2, ref. year 2023	108.66	m2	6743.86	6746.77	-10.62	7.71	External walls and facade
A1-A3	Damp insulation PE, 0.2 kg/m2, EN15804+A2, ref. year 2023	108.66	m2	48.89	49.94	-1.07	0.0179	External walls and facade
A1-A3	Gypsum interior plaster, 900 kg/m3, EN15804+A2, ref. year 2023	2.537	m3	308.43	311.29	-2.98	0.12	External walls and facade
A1-A3	Mineral wool (facade insulation), 46.25 kg/m3, EN15804+A2, ref. year 2023	27.061	m3	1812.41	1798.09	13.32	1	External walls and facade
A1-A3	Lime paint, 0.15-0.25 kg/m2, 1700-1900 kg/m3, EN15804+A2, ref. year 2021	3.383	m3	5675.97	5648.87	25.05	2.05	External walls and facade
A1-A3	Sand-lime brick, 2000 kg/m3, EN15804+A2, ref. year 2023	29.598	m3	9225.65	9213.24	4.25	8.16	External walls and facade
A1-A3	Extruded polystyrene (XPS), 32 kg/m3, EN15804+A2, ref. year 2023	8.87	m3	904.91	900.84	3.81	0.259	External walls and facade
A1-A3	Sum			24720.12	24669.04	31.76	19.3169	External walls and facade
A1-A3	Roof tile, 45 kg/m2, EN15804+A2, ref. year 2021	114.08	m2	1836.68	1828.03	7.37	1.29	Floor slabs, ceilings, roofing decks, beams and roof
A1-A3	Solid construction timber (15% moisture / 13% H2O content), 529 kg/m3, 15% moisture content, EN15804+A2, ref. year 2023	0.71	m3	-446.85	152.79	-600.57	0.921	Floor slabs, ceilings, roofing decks, beams and roof

A1-A3	Ready-mix concrete C25/30, C25/30, 2300 kg/m3, EN15804+A2, ref. year 2023	32.048	m3	7103.66	7106.72	-11.18	8.12	Floor slabs, ceilings, roofing decks, beams and roof
A1-A3	Dry floor screed, gypsum fiber board, 25 mm, 24.07 kg/m2, 960 kg/m3, EN15804+A2, ref. year 2023	234.59	m2	4405.49	4391.07	11.9	2.52	Floor slabs, ceilings, roofing decks, beams and roof
A1-A3	Mineral wool (facade insulation), 46.25 kg/m3, EN15804+A2, ref. year 2023	18.252	m3	1222.43	1212.77	8.98	0.676	Floor slabs, ceilings, roofing decks, beams and roof
A1-A3	Gypsum wallboard, 100 mm, 84 kg/m2, 840 kg/m3, EN15804+A2, ref. year 2023	114.08	m2	2691.25	2685.24	4.38	1.62	Floor slabs, ceilings, roofing decks, beams and roof
A1-A3	Gypsum fiber board, 25 mm, 24.07 kg/m2, 960 kg/m3, EN15804+A2, ref. year 2022	114.08	m2	837.8	834.12	3.5	0.181	Floor slabs, ceilings, roofing decks, beams and roof
A1-A3	Extruded polystyrene (XPS), 32 kg/m3, EN15804+A2, ref. year 2023	5.948	m3	606.81	604.08	2.56	0.174	Floor slabs, ceilings, roofing decks, beams and roof
A1-A3	Sum			18257.27	18814.82	-573.06	15.502	Floor slabs, ceilings, roofing decks,

								beams and roof
A1-A3	Gypsum interior plaster, 900 kg/m3, EN15804+A2, ref. year 2023	3.44	m3	418.21	422.09	-4.04	0.163	Internal walls and non-bearing structures
A1-A3	Sand-lime brick, 2000 kg/m3, EN15804+A2, ref. year 2023	22.844	m3	7120.44	7110.86	3.28	6.29	Internal walls and non-bearing structures
A1-A3	Galvanized steel stud framing profiles per m2 (air gap included), UD and CD profiles included, wing width: 6 mm, flange width:50 mm, steel thicnkess:0.6 mm (23 gauge), 450 mm spacing, 2.4 kg/m2, One Click LCA	531	kg	1723.37	1712.48	8.7	2.2	Internal walls and non-bearing structures
A1-A3	Gypsum plaster board, fire resistant, 12.5 mm, 10 kg/m2, EN15804+A2, ref. year 2023	53.805	m2	91.9	123.91	-32.14	0.14	Internal walls and non-bearing structures
A1-A3	Sum			9353.92	9369.34	-24.2	8.793	Internal walls and non-bearing structures
A1-A3	Ready-mix concrete C25/30, C25/30, 2300 kg/m3, EN15804+A2, ref. year 2023	0.47	m3	104.18	104.22	-0.164	0.119	Other structures and materials
A1-A3	Railing and fencing, calculated average for Germany, 40 kg/m, One Click LCA	6.79	m	622.93	623.82	-1.2	0.312	Other structures and materials
A1-A3	Sum			727.11	728.04	-1.364	0.431	Other structures and materials

A1-A3	Wooden doors, calculated average for Germany, 1.23x2.18 m, 36 kg/m2, 96 kg/unit, One Click LCA	21.81	m2	382.98	1268.25	-910.35	25.08	Windows and doors
A1-A3	Aluminium frame window triple glazed, operable(tilt and turn), 0% recycled aluminium, 1.48 m x 2.18 m, 32.6 kg/m2, One Click LCA	40.34	m2	6878.46	6817.46	58.49	2.51	Windows and doors
A1-A3	Medium density fibreboard (MDF), 700 kg/m3, KRONOSPAN GmbH	0.471	m3	-328.06	184.63	-513.39	0.702	Windows and doors
A1-A3	Sum			6933.38	8270.34	-1365.25	28.292	Windows and doors
Subtotal for A1-A3:				**65669.54**	**67531.77**	**-1941.044**	**78.8249**	