Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Architecture and Design
Department of Architecture and Technology

Theresa Sophie Reif

Evaluation of Early-Phase Building LCA Tools

Assessment of the Accuracy and Applicability of 'Automodel by Reduzer' and 'Carbon Designer 3D by One Click LCA' in Evaluating GHG Emissions of Buildings

Master's thesis in Sustainable Architecture
Supervisor: Dr. Eirik Resch
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Abstract

The construction sector contributes significantly to anthropogenic climate change through greenhouse gas (GHG) emissions. Therefore, it is important to reduce operational and embodied emissions from structures. The thesis focuses on the consideration of embodied emissions from building materials. Life Cycle Assessment (LCA) calculation tools enable informed decision-making toward increased sustainability during the design process. The initial design phase of buildings wields significant influence over the buildings' emissions throughout their lifecycle. However, the lack of information at an early-phase regarding design specifics and their potential impact on emissions presents a challenge for sound guidance. Formulating parametric models as the basis for GHG calculations is an important strategy to fill in knowledge gaps that include design decisions not yet made in the conceptual design phase. This study delves into exploring and assessing the tools 'Automodel' by Reduzer and 'Carbon Designer 3D' by One Click LCA (OCL) through two case studies. The tools focus exclusively on calculating the material-associated Global Warming Potential (GWP) for the main building and are user-friendly with intuitive interfaces. Supplemented by a comprehensive literature review, this study elaborates on the essential parameters required for a meaningful estimation of early-phase GHG emissions. These are: Generating a simplified model, though representing the complexity of the design appropriately; Developing a complete building model where initially unknown parameters are augmented with assumptions to allow for consistent scope throughout the process; Using predefined standardized component structures with generic data sets; Including sensitivity information about the results. In terms of prediction accuracy, Reduzer's Automodel and OCL's Carbon Designer 3D have the potential to support planning decisions, albeit with limitations in producing accurate predictions of the total GWP. Carbon Designer 3D excels at visualizing designs, while Automodel allows for the creation of complex geometries. However, there is room for improvement in both tools. E.g., Automodel can be improved as follows: More accurate consideration of internal walls; Use of generic material data; Representation of building complexity in one model without requiring multiple versions; Use of checkboxes to query additional design features; Inclusion of uncertainty ranges for calculation results; Optimization of usability through easier component switching and a graphical representation of the parametrically generated model.

Keywords

Early-Phase Building LCA, Carbon Footprint, Embodied Emissions of Buildings, Building Design Process, Parametric Building LCA Model, Building LCA Tools, Carbon Designer 3D by One Click LCA, Automodel by Reduzer

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List of Abbreviations

AIE	ATHENA Impact Estimator©
API	Application Programming Interface
BIM	Building Information Modelling
BOM	Bill of Materials
BREEAM	Building Research Establishment Environmental Assessment Methodology
BPIE	Building Performance Institute Europe
°C	Degrees Celsius
CO_2	Carbon Dioxide
COP21	UN Climate Change Conference
DGNB	Deutsche Gesellschaft für Nachhaltiges Bauen (German Sustainable Building Council)
EP	Eutrophication Potential
EPD	Environmental Product Declaration
EU	European Union
eq	Equivalent
GFA	Gross Floor Area
GHG	Greenhouse Gas
GlobalABC	Global Alliance for Buildings and Construction
GSA	Global Sensitivity Analysis
GWP	Global Warming Potential
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
LC	Life Cycle
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCSA	Life Cycle Sustainability Assessment
LCIA	Life Cycle Impact Assessment
LEED	Leadership in Energy and Environmental Design
LOD	Level of Detail
LOG	Level of Geometry
LOI	Level of Information
MEP	Mechanical, Electrical, Plumbing
NTNU	Norwegian University of Science and Technology

OCL	One Click LCA™
ODP	Ozone Depletion Potential
PENRT	Total Use of Non-Renewable Primary Energy Resources
PERT	Total Use of Renewable Primary Energy Resources
PV	Photovoltaic
SDG	Sustainable Development Goal
sLCA	Social Life Cycle Assessment
UN	United Nations
UNEP	United Nations Environment Programme
WWR	Window-to-Wall Ratio
ZEB	Zero-Emission Building

1 Introduction

The Intergovernmental Panel on Climate Change (IPCC) publishes status reports every five to six years that are considered the scientific consensus statement regarding the influence of humans on the world's climate. The latest publication from 2023 begins with the following statement:

> *"Human activities, principally through emissions of greenhouse gases, have unequivocally caused global warming, with global surface temperature reaching 1.1°C above 1850–1900 in 2011–2020. Global greenhouse gas emissions have continued to increase, with unequal historical and ongoing contributions arising from unsustainable energy use, land use and land-use change, lifestyles and patterns of consumption and production across regions, between and within countries, and among individuals (high confidence)." [1, p. 4]*

According to the report, human-induced climate change is therefore undeniable. The report further states that net zero CO_2 emissions will be required to limit global warming - it is therefore still within humans' power to prevent catastrophic impacts from climate change if we act within this decade.

In the Paris Agreement, 196 parties signed a legally binding international treaty on climate change at the UN Climate Change Conference (COP21) on December 12th, 2015. The agreement's overall objective is to limit "*the increase in the global average temperature to well below 2°C above pre-industrial levels*" and continue efforts "*to limit the temperature increase to 1.5°C above pre-industrial levels.*" [2] However, reaching the goal "*involves rapid and deep and, in most cases, immediate greenhouse gas (GHG) emissions reductions in all sectors this decade*" [1, p. 21, 2] As stated above, global warming is caused by factors such as energy consumption, land-use and land-use change, lifestyle, consumption, and production. These are all areas that are particularly relevant in the construction sector. According to the International Energy Agency (IEA), the **built environment is responsible for around 40% of global CO_2 emissions each year**. Of these total emissions, the operation of buildings causes 27 % per year, while the building and infrastructure materials and construction (so-called embodied carbon) are responsible for the remaining 13 % per year. [3]

The Building Performance Institute Europe (BPIE) provides a tracker to monitor the progress of the ambitious yet urgently needed goal to achieve climate neutrality in buildings by 2050. It presents the current status of the goal in Europe but focuses on only the operational emissions of buildings.

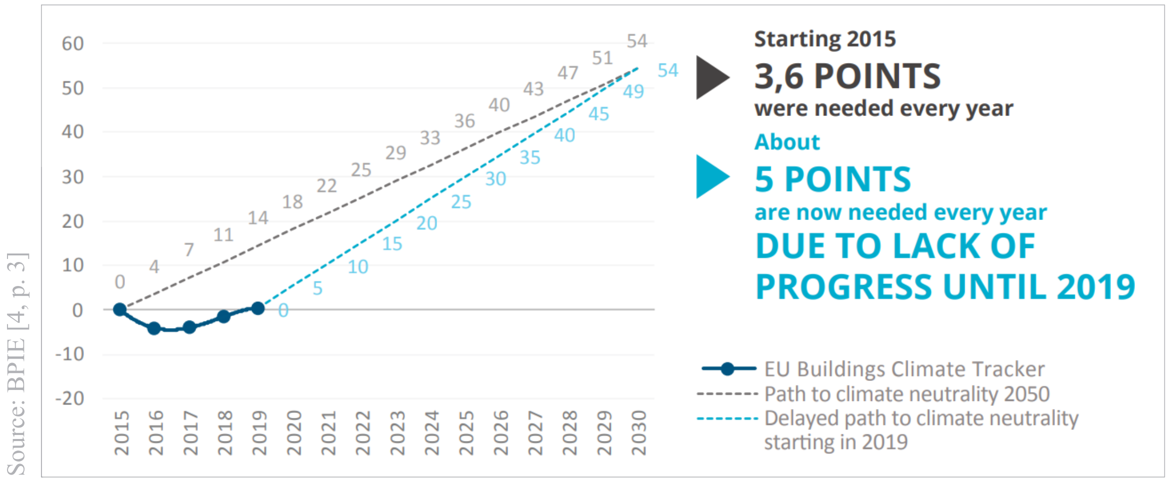


Figure 1 EU Buildings Climate Tracker and the path to climate neutrality in 2050

As shown in **Figure 1** there was no improvement in the climate neutrality of the building sector in Europe between 2015 and 2019. GHG emissions worsened and returned to 2015 levels (dark blue line). Due to the lack of progress, the path to climate neutrality until the 2030 milestone becomes steeper as of 2019 (light blue line compared to grey line). [4] BPIE further states: *"The EU must immediately, rapidly, and strongly accelerate the rate of building decarbonisation. Progress must be drastically increased if the EU is to reach climate neutrality in 2050 in the building stock."* [4, p. 1]

According to a 2019 report by the Organization for Economic Cooperation and Development (OECD), the global consumption of raw materials will almost double by 2060 as the world economy grows and living standards rise, exacerbating the environmental overloading we are experiencing today. The environmental consequences will be significant. Thus, **material management activities will be responsible for two-thirds of all GHG emissions** and account for 50 Gt CO_2-eq. **by 2060** [5]. The reports predict the following: *"The volume of concrete use is so large that even relatively low per kg impacts imply large consequences: concrete production accounts for 12% of total GHG emissions in 2060, and the production of metals for 12%"* [5, p. 16]. As shown in **Figure 2**, construction materials are set to dominate resource consumption in fast-growing developing economies, with building material-related emissions projected to increase by 3.5 to 4.6 Gt CO_2-eq./year by 2060.

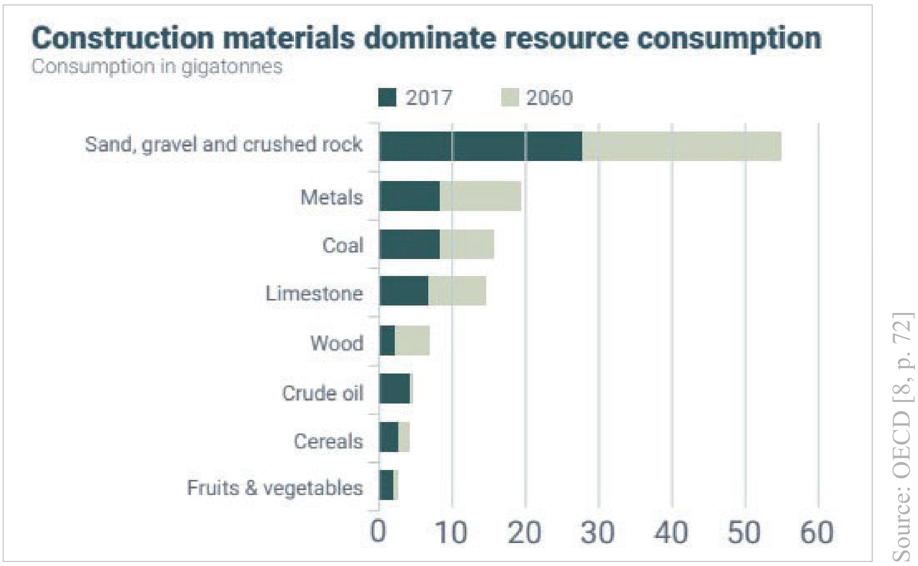


Figure 2 Construction materials dominate resource consumption.

All this information demonstrates that man-made climate change can be counteracted if drastic actions are taken immediately. Especially in the building sector, which is responsible for almost 40% of total GHG emissions, a significant amount of resource consumption, waste generation, etc., major steps can be taken towards climate neutrality, a process that urgently needs to be accelerated. This calls for higher energy efficiency and climate-neutral energy generation during the operational phase of buildings but measures for climate-neutral material extraction and sufficiency are also crucial parameters.

The carbon footprint analysis of structures, such as buildings, is facilitated through the utilization of GHG balances, a pivotal component of Life Cycle Assessments (LCA). By scrutinizing the full environmental impacts of a building's life cycle (LC), spanning from initial raw material extraction to eventual demolition, stakeholders and designers are empowered to proactively identify and implement strategic measures that mitigate unsustainable consequences [6]. The engagement of all relevant stakeholders in the LCA process fosters a comprehensive approach to decision-making, allowing architects, engineers, investors, occupants, and regulatory bodies to collaboratively comprehend sustainability objectives. This collective effort lends itself to optimizing design, material selection, energy efficiency, and waste management, underscoring the significance of early-phase building LCA [7].

According to the Global Status Report for Buildings and Construction by the UN Environment Program, there are two primary methods for conducting carbon footprint assessments. The first approach involves intricate calculations executed by experts, often utilizing advanced simulations. This method necessitates substantial expertise and is typically carried out during later project stages when comprehensive project knowledge is available. An alternative method is simplified carbon accounting, which offers basic insights into GHG trends within the project and is suitable for all stakeholders [8]. However, during the early architectural design phase, when pivotal decisions pertaining to carbon neutrality are made, precise GHG balance data might be lacking, casting doubt on the assessment's validity. This challenge highlights the importance of identifying available information in the initial phase, determining the roles of various parameters in a reliable GHG balance, and integrating these parameters into the assessment. Additionally, proper guidance for result evaluation is pivotal to translating GHG balance predictions into informed decisions.

Until recently, science has focused on optimizing energy efficiency during the operating phase. However, energy is required and GHG is emitted also during the production, transportation, construction process, dismantling, and disposal of building materials. It is therefore important to shift the focus toward embodied emissions since operational emissions have been in the focus and energy efficiency of new buildings has improved at the cost of higher embodied emissions [9]. The present work focuses on the reduction of embodied emissions in buildings from an early design stage on.

1.1 What is LCA?

Building LCA is a methodology used to evaluate the impacts of a building throughout its entire life cycle, from the extraction of raw materials to the end of its useful life and eventual disposal (see **Figure 3**). When a life cycle sustainability assessment (LCSA) is carried out, it is structured according to the three pillars of sustainability: social responsibility, economic efficiency, and ecology [10]. Whereas social life cycle assessment (sLCA) analyzes social responsibility, life cycle costing (LCC) considers the economic aspects and environmental life cycle assessment (LCA) reflects ecological management [11]. This work focuses on the ecology of a construction project. LCA considers factors such as energy and resource consumption, GHG emissions, and waste generation. Building LCA can help inform decisions related to building design, construction, and operation to minimize environmental impacts and promote sustainable development.

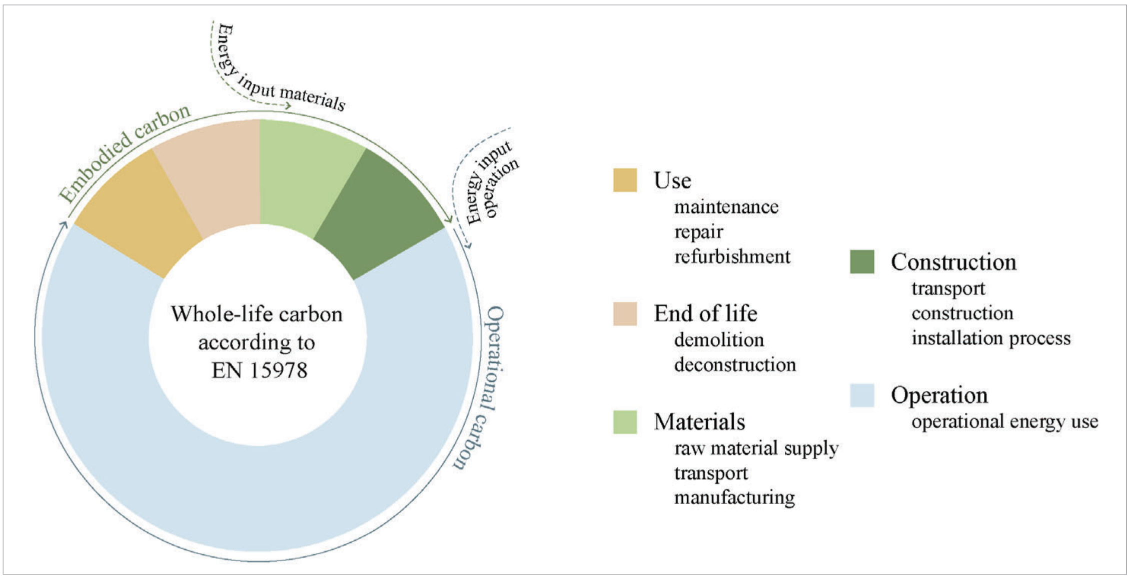


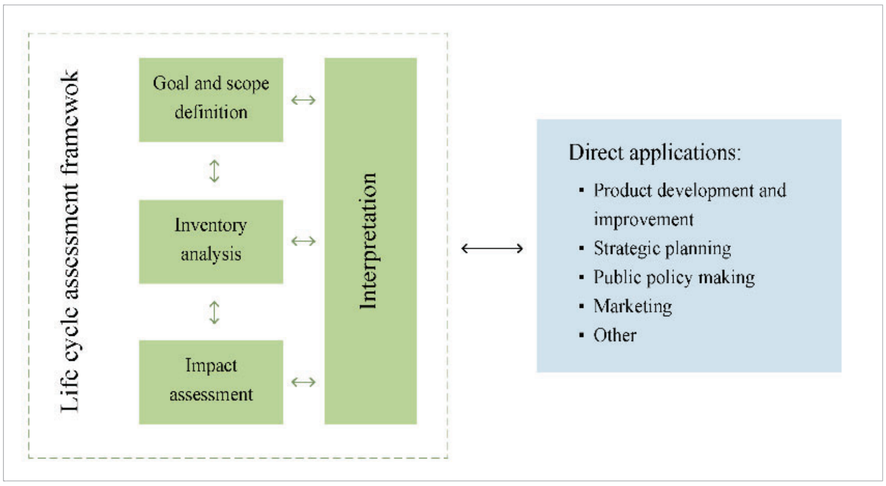
Figure 3 Carbon life cycle according to EN 15978

Whole-life carbon can be distinguished into embodied carbon and operational carbon. **Embodied carbon** refers to the total amount of GHG emitted during the production, transport, and disposal of building materials and construction processes. It includes the direct emissions generated by manufacturing, as well as those associated with energy use during transportation, and construction. Embedded carbon not only includes the embodied carbon of building materials, but also the emissions associated with ongoing maintenance, repair, and replacement over the building's lifespan. [12]

Operational carbon, on the other hand, refers to the carbon emissions generated during the use and operation of a building. This includes energy consumption for heating, cooling, lighting, and other building services, as well as the emissions associated with the use of appliances, equipment, and transportation related to the building's operation. Operational carbon is a crucial component of building LCA, as it represents a major source of GHG emissions, as shown in **Figure 3**, that can be mitigated through energy-efficient design, renewable energy sourcing, and other strategies.

1.1.1 Principles of LCA

The general LCA principles are internationally defined in the standard ISO 14040:2006. Its rules can also be transferred to building LCA. According to the standard, an LCA is performed with the following four phases [13]:



Source: Own illustration according to ISO 14040:2006 [13]

Figure 4 Stages of an LCA according to ISO 14040:2006

(1) **Goal and Scope Definition:** The purpose and the extent of the study are defined considering the end use of the building, the geographic location, and the expected service life. Accordingly, the spatial system boundary (defining the elements considered such as mechanical, electrical, plumbing (MEP), transportation, outdoor facilities etc.) and the temporal system boundary (study period and LC phases considered) are established. In addition, a reference unit and the end-of-life scenario are defined. Also, a precisely formulated research question should be posed, and a baseline scenario formulated to define the goal of the LCA.

(2) **Inventory Analysis:** The inputs and outputs of the building's LC stages are quantified and characterized. The input parameters include the product inventory (material flow) and the inventory of building operations. The former is linked to the Bill of Materials (BOM), the selected materials and the service life of the building parts. The latter includes the energy demand calculation and the source of energy. Based on the inventories, an input-output balance can then be drawn. This can have different focal points, such as resource consumption, (non-)renewable primary energy demand, or waste.

(3) **Impact Assessment:** The potential environmental impacts of the building's LC stages are evaluated considering various impact indicators such as global warming potential (GWP), ozone depletion (ODP), eutrophication potential (EP), etc. Accordingly, the BOM is converted into units from EPDs (Environmental Product Declaration)/generic databases and optionally is normalized or weighted.

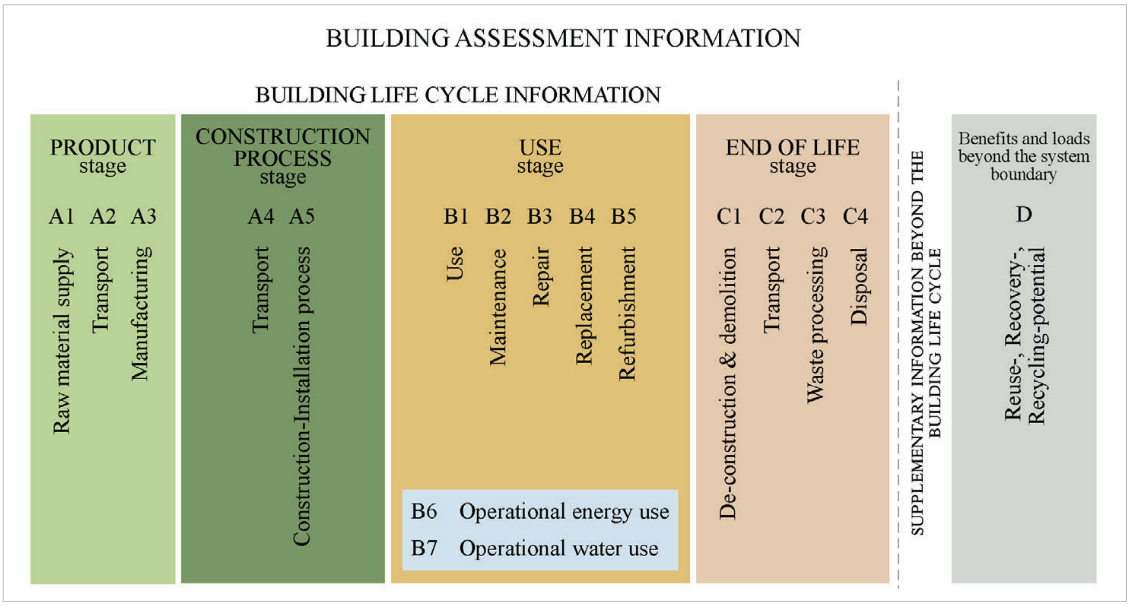
(4) **Interpretation:** The results of the inventory analysis and impact assessment are interpreted to identify the significant environmental aspects of the building LC and to provide recommendations for improvement. In this step, the research question from phase (1) will be answered. This can be done by comparing different scenarios. Phase (4)

therefore involves drawing a conclusion, communicating the limits, and making a recommendation.

In the case of certification according for example DGNB, BREEAM or LEED, **documentation** of the LCA process and results is another important task.

1.1.2 Methodology of LCA

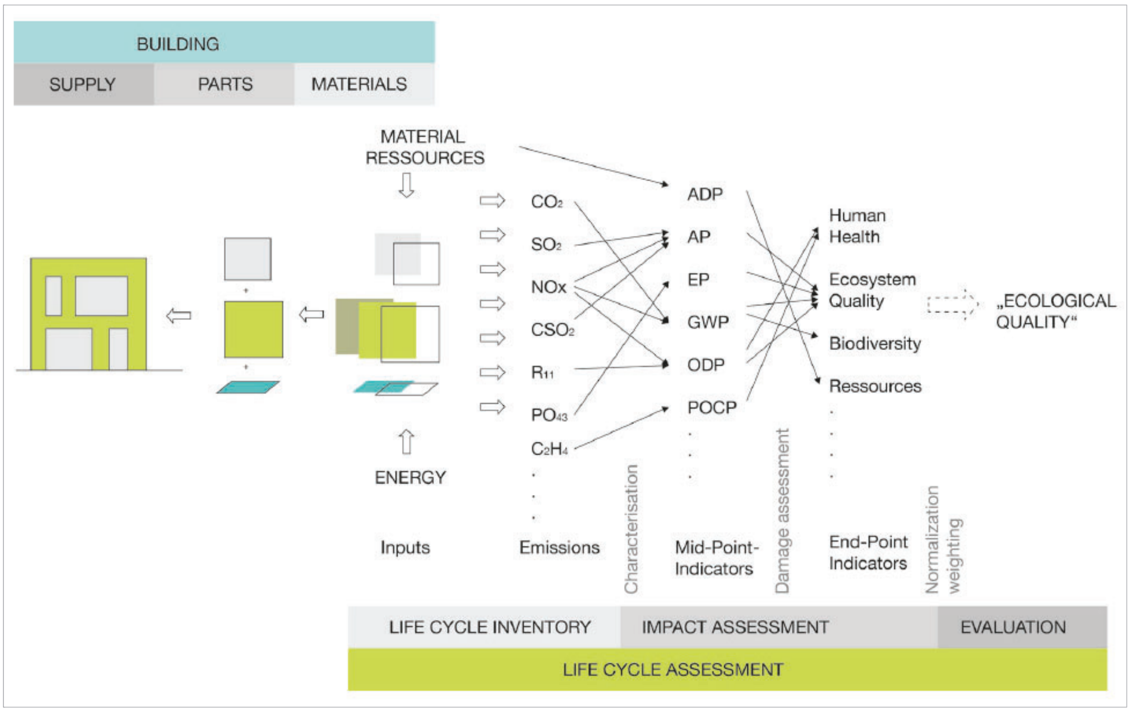
The international standard ISO 14044:2006 is a widely recognized international standard that provides principles, requirements, and guidelines for conducting an LCA of a product or service. EN 15978:2011 is based on ISO 14044:2006 but adds further requirements and recommendations specific to building LCA. It provides a method for calculating the environmental impact of a building through the use of LCA, based on the functional unit of the building (e.g., per m² or occupant). EN 15978:2011 considers environmental impacts in different stages of the building LC, including production (A1-A3), construction (A4-A5), use (B1-B7), and end of life (C1-C4). Additionally, it considers benefits and loads beyond the system boundary (D) expressed by the reuse, recovery, and recycling potential (see **Figure 5**). [14]



Source: Own illustration according to EN 15978:2011 [14]

Figure 5 The different stages of a building LCA

There are two different approaches to conducting an LCA. First, (i) the static approach, which is commonly used and does not consider changes during the building's lifetime. Second, (ii) the dynamic approach. This considers, among other things, the future change in energy production and therefore the different GHG intensity from the electricity grid, the future reduction of embodied emissions due to technical progress in material technology, possible impacts of climate change in the future, a change in user behavior, or the use of new technologies and materials. The static approach is easier to perform, due to its reduced complexity, but the result can differ significantly from reality, comparing the progress in building technology over the last decades. For example, the Zero Emission Building (ZEB) project report of 2016 proposes a 50% reduction of the environmental impact of photovoltaic (PV) modules in scenario B4 (replacement) relative to the new acquisition in A1-A3 as a rule of thumb to account for the ongoing development of PV plants. [15, p. 28]



Source: ©Patricia Schneider-Marin [79]

Figure 6 LCA process from building model to LCA indicators to evaluation.

As described in Chapter 1.1.1, an LCA is conducted in four phases. After the goal and scope definition, phases 2 and 3 follow. In phase 2, a BOM (mass list of the various components of the building) is created. The various elements are then linked with information on, for example, service life and material specifications (e.g., from generic databases, or EPDs). The entirety of the information results in the LC inventory (LCI). This phase is followed by the assessment of impacts at each LC level (**Figure 5**) in phase 3, to evaluate various indicators such as human health, ecosystem quality, biodiversity, or resource use. In this process, environmental interventions are qualitatively assigned to impact categories, such as abiotic depletion potential (ADP), soil and water acidification potential (AP), eutrophication potential (EP), GWP, etc. These impact categories are quantified in a common unit according to EN 15084:2012 so that the result of the indicator can be summarized in one number. [16] In the final, optional step, weighting can evaluate the ecological quality of the building project (see Figure 6).

1.2 Task and Objectives

The overarching objective of this study is to formulate a scientific framework for parametric LCA calculations in the early design phase of building projects, aiming to effectively curtail material-associated GHG emissions. Through a comprehensive review of existing literature, this study elucidates key parameters concerning early-phase LCA calculations. A comparative analysis of prevalent early-phase LCA tools, namely "Automodel by Reduzer" and "Carbon Designer 3D by OneClick LCA," offers insights into their accuracy, user-friendliness, and scope in assessing GHG emissions. Building on these insights, the study proposes enhancements to the "Automodel by Reduzer" tool, enabling its broader application even among non-experts, to optimize building designs for zero carbon emissions. In conclusion, this research endeavors to conclude the following research questions:

Q1 *What are the decisive parameters of early-phase LCA in current research?*

Q2 *How do the parametric early-phase LCA tools "Automodel by Reduzer" and "Carbon Designer 3D by OneClick LCA" differ in terms of accuracy, usability, and scope in assessing GHG emissions?*

Q3 *How can Reduzer be further improved to enhance its applicability?*

1.3 Limitations

The environmental impact of a construction project can be represented with the help of an LCA. However, this paper focuses on the GHG balance which is depicted by the global warming potential (GWP). In addition, only embodied emissions are considered in the analysis of the GWP. Emissions that occur during the operation of the building, e.g., through heating or electricity use, are not part of this work. Other indicators such as the Acidification potential (AP), the Abiotic depletion potential (ADP), etc. are also not the subject of this work. Nevertheless, it is important to mention that for a holistic ecological consideration of the impacts of construction projects, looking also at other indicators is strongly recommended.

2 Current State of Research

For a better understanding of this thesis, scientific basics about project phases of buildings are explained in this chapter. Furthermore, the GHG emissions calculators Reduzer and One Click LCA are presented. A comparison with alternative early-phase LCA tools will give a current market insight. In addition, this chapter provides an overview of the findings that can be drawn from the literature for the development of the parametric model for early-phase LCA.

2.1 LCA in the Construction Project Phases

A project is characterized by its novelty and uniqueness. It has a defined initial objective and a limited time frame and resources to achieve the goal. [17, p. 5] From the starting point where the construction project is commissioned, the final goal is to create a finished building that is tailored to the needs and requirements of the user. Along the way, a multitude of trades and stakeholders are involved and must be coordinated. To best manage the interactions of these different stakeholders and to ensure agreements and communication to achieve the best possible result, various organizations have published guides to the process chain of a construction project. When carrying out an LCA, it is also of utmost importance to know the process of a construction project. Only then can it be determined at what point in time decisive decisions are made and, consequently, an LCA will have the greatest possible impact on the construction project. In Norway, Bygg21, a cooperation between the construction industry and the Norwegian government, defines the construction process in eight phases. Starting from (1) the strategy definition to (2) the project and concept development, (3) the further development of the selected concept, (4) the detailed design, (5) the production and transportation, (6) the completion, handover and commissioning, (7) utilization and management, and finally to (8) the liquidation [18]. In the UK, the RIBA plan of work has been defined by the Royal Institute of British Architects, which is fairly similar to the Bygg21 process. Though, it does not take the liquidation at the end of a project into account, it adds another phase to Bygg21's phase 4, the Detailed Design. Here, RIBA adds Spatial Coordination to test and validate the architectural concept, to ensure that the architectural and engineering planning of phase 2 is coordinated before creating the technical design for manufacturing and production [19]. In Germany, the process is divided into nine service phases according to HOAI (Honorarodnung für Architekten und Ingenieure - Fee Scale for Architects and Engineers).

Table 1 Comparison of different building project phase models and determination of early and detailed design (own representation)

design phases	HOAI (Germany) [17]	RIBA (UK) [16]	Bygg21 (Norway) [15]
early design	LPH 1 Basic evaluative (Grundlagenermittlung)	0 Strategic Definition	Strategic Definition (Strategisk Definisjon)
early design	LPH 2 Preliminary planning (Vorplanung)	1 Preparation and Briefing	Project and concept development (Program- og konseptutvikling)
early design	LPH 3 Design planning (Entwurfsplanung)	2 Concept Design	Further development of the selected concept (Bearbeiding av valgt konsept)
detailed design	LPH 4 Approval planning (Genehmigungsplanung)	3 Spatial Coordination	Detailed Design (Detaljprosjektering)
detailed design	LPH 5 Execution planning (Ausführungsplanung)	4 Technical Design	
detailed design	LPH 6 Preparation of contract awarding (Vorbereitung der Vergabe)		
detailed design	LPH 7 Participation of contract awarding (Mitwirkung bei der Vergabe)		
	LPH 8 Object supervision (Objektüberwachung)	5 Manufacturing and Construction	5. Production and Transportation (Produksjon og Leveranse)
	LPH 9 Object management (Objektbetreuung)	6 Handover	6. Handover and commissioning (Overlevering og ibruktakelse)
		7 Use	7. Utilization and management (Bruk og forvaltning)
			8. Liquidation (Avvikling)

As shown in **Table 1**, the various definitions of a construction project according to Bygg21, RIBA, and HOAI as example guidelines from Norway, the UK and Germany, differ primarily in the detailing phase, where the various crafts are coordinated, final plans are drawn, and contracts are awarded. The early-phase is fairly similar in all the different guidelines. In this thesis, the early-phase is defined as phases 1, 2 and 3 (Bygg21 phases), as the detail of the design is still on a conceptual level. However, the line between the early design phase and the detailed design phase is blurry and cannot be drawn strictly, as a design process never occurs linearly (see **Figure 7**). After the early-phase design, the detailed design follows in phase 4, where a selected concept is processed in depth until it can be approved and awarded for production and construction.

2.1.1 Design Process and Decision-Making

According to Lawson [20]; who studied the design process by doing a literature review, interviewing designers, executing a laboratory study of design students, and experimenting with experienced designers; a design process is rather complex with a sequence of activities included. Designers need to study the requirements, produce one or more solutions, test them against direct and indirect conditions and communicate the design to all stakeholders. However, Lawson questions whether the sequence always has the same order and whether these activities proceed separately from each other. The design exists more as a process in which problem and solution are created together. Any simplification of a design process will not illustrate the highly complex mental process. Nevertheless, the following **Figure 7** attempts to illustrate the process, which is not linear but rather resembles a tangled ball of wool. Decisions are taken back, revised, further developed, and possibly discarded again.

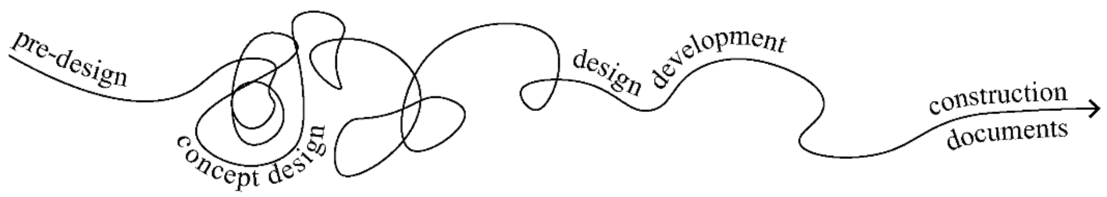


Figure 7 Exemplary course of a design process

It is therefore expected that many fundamental decisions are made in the early-phase (the concept design), where the path is chaotically tangled. As the process continues, the design is refined, but no fundamental upheavals are predicted.

In the beginning, the client's goals and space requirements are set. It is up to the architects to guide the client and to identify potentials and challenges. In the **pre-design**, much information is gathered, which will be the foundation for the concept design development which follows. The goal is to learn everything about legal and client requirements, about the site, and to define the strategies regarding environmental protection, social responsibility, and economic efficiency. Benchmarks can be established, and an overall outcome can get defined [21].

In the **concept design**, the earlier set program is translated into a building design. Many possible solutions are explored and tested. It is the phase in which a general idea of the look and feel is developed, and it is the starting point for designing the building. In the German HOAI, this phase is represented by LPH 2 and LPH 3 which accounts for approximately 22% of the total architectural work and fees of the whole project. [22] The main goal of the concept design is to determine the shape and size of the building. So, in the concept design phase, it is determined how the building should look and function and spacial plans are established. Much sketching and modelling are done during this phase, and numerous meetings are held with the client to set the framework for the entire project. According to Hegger et al., it is highly recommended to also involve technical consultants such as building physicists and structural engineers in the design process, who can guide the construction project to a holistically functioning project. However, the extent of interdisciplinary collaboration varies depending on project characteristics such as structure, size, scope, etc. [23]. Rasmussen also found through interviews in her master's thesis that the involvement of engineers and consultants varies depending on the context and requirements of the project. According to Rasmussen, environmentally ambitious projects are difficult to implement "without involving an environmental consultant from the early project development" [24].

Once the basic design has been established and the architect and client agree, further development of the selected design concept begins where the concept design is refined and e.g., material choices of finishings, etc. get defined. The design process comes to an end with the production of construction documents, like detailed plans, and awarding of contracts to the trades. In summary, it can be stated that fundamental decisions about the building project are made in the early-phase, which consists of the pre-design and the concept design. Basic aspects such as setting benchmarks and goals (e.g., about the carbon footprint, sound insulation, energy standard, etc.), and decisions about geometry, superstructure, spatial planning, and function are determined here.

2.1.2 LCA in the Design Process

The question arises where LCA can have the most effective influence on the project. Looking at the design process and decision-making timeline (see 2.1.1), key decisions and the framework of the project are defined in the early design phase. Big decisions like building new or refurbishing, how much space is required, or which energy standard to achieve are decisive parameters for low environmental impact. However, the information situation at the beginning of a project is problematic, as decisions on e.g., geometry or material use are limited and can change significantly during the project. The reliability of the LCA results is thus questionable due to the high degree of vagueness [25]. Schneider-Marin also addresses this issue and developed the base for following **Figure 8** in her dissertation.

Source: Own representation derived from Schneider-Marin [88]

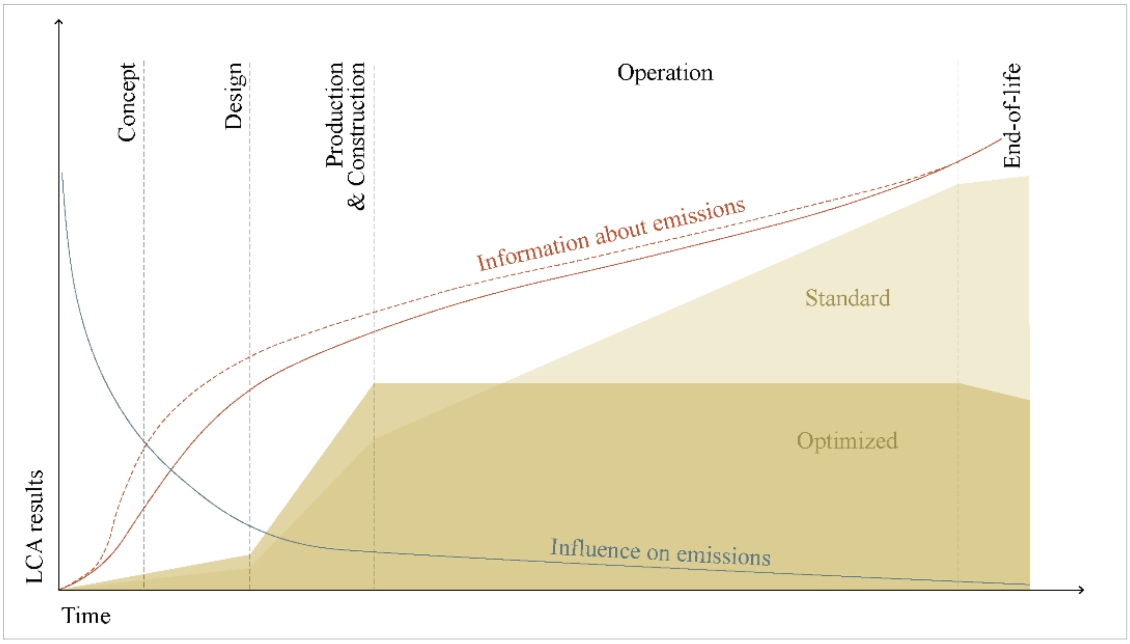
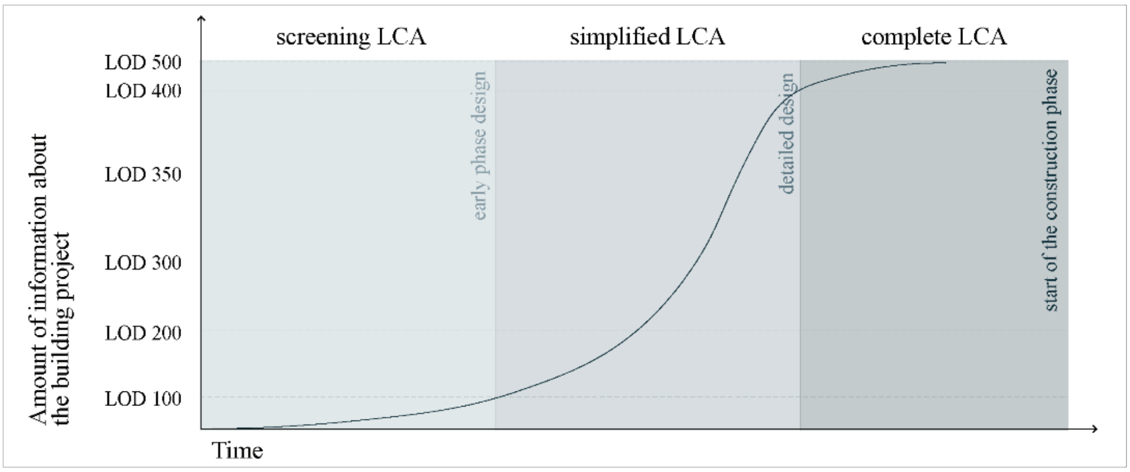


Figure 8 LCA in the building LC. Dashed line: Information in an LCA led design process.

Looking at the environmental impact during the LC of a building (yellow areas in **Figure 8**), the following trend can be observed: After a small increase in environmental impact during the design phase (e.g., due to energy consumption for computers, sample pieces, site visits, etc.), the environmental impact increases rapidly during production and construction due to manufacturing, production, and transportation (phases A1-A5). If the building is optimized in terms of energy efficiency and renewable energy production, no or only low emissions occur during operation. However, if standard operating technologies and basic thermal insulation standards are applied, environmental impacts can increase sharply during the operation phase. At the end of the service life, environmental impacts can either increase, e.g., through disposal by incineration or decrease, e.g., through reuse and recycling of building materials.

Accordingly, due to the scarce information in the early design phase, the main challenge is to simplify the LCA methodology as much as necessary, but as little as possible, to achieve meaningful LCA calculation results at an early stage and thus be able to lead the construction project to a zero-emission building (ZEB). A ZEB is defined to generate sufficient renewable energy to offset the building's GHG emissions over its lifetime [26]. As Meex et al. found through a literature review of the state of the art regarding simplifications of LCA [27], the EeBGuide (Operational Guidance for Life Cycle Assessment

Studies of the Energy Efficient Buildings Initiative, funded by the European Commission Research & Innovation Environment) [28] is the base for most methodological LCA simplifications. EeBGuide focuses primarily on the calculation of LCA and input data but also includes recommendations for output data and communication. Here, three levels of detail are generally distinguished: (1) screening LCA, (2) simplified LCA, and (3) complete LCA. These types of LCAs are based on the level of detail and information available in the design process, in particular, concerning the material-related information specification (from basic material category information in the early design phases to more detailed product information in the developed design phase). The **screening LCA** is designed for use in the pre-design phase and concept design phase of the building – therefore **in the early design phase**. The simplified LCA meets the requirements of various certification systems such as DGNB. It accompanies the detailed design phase and the phase of producing construction documents. The complete LCA is performed after the design phase has finished and all design parameters are set [28].



Source: Own representation derived from Llatas, Meex, and Safari [11, 27, 32]

Figure 9 Relation between design phases of buildings (defined in 2.1), the level of detail (LOD) of a BIM model, and level of simplification of LCA according to the EeBGuide.

Figure 9 uses the classification of LOD 100 to LOD 500 connected to building information modelling (BIM) methodology [29] and defines the minimum required geometrical information (level of geometry - LOG) and data information (level of information - LOI) of the computational model. LOG and LOI together describe the sensitivity of the model. Generic objects are used in the early design phase, whereas high-resolution and defined object information is available in the detailed design phase. The precision of the modelling becomes more pronounced as the design process progresses [30]. The following **Table 2** shows the definition and available data at different LOD levels according to the BIM-Forum.

Source: Own representation according to BIMForum [83]

Table 2 Definition and available data at LOD levels

LOD	Definition	Available data
100	Generic representation of the element	Approximate size and volume of the building
200	Generic system, object, or assembly	Approximate size, shape, quantities, location, and orientation
300	Specific system, object, or assembly	Quantity, size, shape, location, and orientation
350	Specific system, object, or assembly	Quantity, size, shape, location, orientation, and interfaces with other building systems
400	Specific system, object, or assembly	Quantity, size, shape, location, orientation with detailing, fabrication, assembly, and installation information
500	Field verified representation	Quantity, size, shape, location, and orientation, might also include non-graphic information

According to Cavalliere [31] LOD 500 is rarely achieved during the design process in practice because the modelling effort is enormous and in the model with LOD 500 the components are displayed exactly as they are in the as-built status. According to Safari [32], LOD 100 corresponds to screening LCA using generic data. For conducting a simplified LCA, the LOD should be above LOD 100 and below LOD 400. However, the components of a building model rarely all have the same LOD. Rather, the classification shows the LOD of the majority of components in a model [31, 32, 11].

2.2 Early-Phase LCA

This chapter discusses the particularities of early-phase LCA. At the beginning, screening LCA is introduced and uncertainties in the early-phase are discussed. Subsequently, different early-phase LCA calculation tools on the market are presented and compared to each other.

2.2.1 Screening LCA

To gain an initial understanding of the impacts of the construction project, screening LCA can be an adequate method. According to the EeBGuide [28], which is widely used [27], screening LCA is a simplification of the LCA methodology according to ISO 14044. It often does not represent all LC phases of a building and results are likely to be based on general assumptions, depending on the objective and scope of the study. However, the data is only representative if the geography, technology, age, time, and precision are comparable to the project of application [28]. As the EeBGuide further states, screening LCA focuses usually on some indicators but neglects many others. It recommends focusing on the GWP, the total use of non-renewable primary energy resources (PENRT) and the total use of renewable primary energy resources (PERT). Considering the required simplifications for screening LCA in the early-phase, it is not possible to obtain a detailed result and thus, the results cannot be compared with the final LCA results of the project. The EeBGuide recommends comparing the screening LCA results internally but advises not to publish the results. Hence, a screening LCA provides an estimation of the environmental impact which allows environmental hot spots to be identified but requires additional in-depth assessment later in the process. Architects can then revise their designs according to the results already in the early-phase to optimize the environmental performance of the project.

2.2.2 Uncertainty in Early-Phase LCA

The planning of a building object is associated with uncertainties and changes during the process already from the initial phase until the end of the construction phase and sometimes even beyond [33]. Especially in the early stages, it is of great importance to reduce uncertainties in the LCA process to obtain reliable LCA results to be able to support decision-making [32]. During a construction project, various uncertainties occur. They can result from accidents, due to changes in the process, lack of awareness, or lack of information [34]. Therefore, an uncertainty analysis is important to evaluate the contribution and sensitivity of the parameters [32]. Rezaeia et al. [35] studied the uncertainty of materials in each assembly, using Monte Carlo iterations, where the building design or assembly of components is randomly sampled. They found, that early design LCA in the LOD 100 stage has a corresponding uncertainty to the LOD 300 stage. This shows that a more detailed design does not necessarily lead to a more accurate LCA prediction, or in other words: an early-phase LCA does not necessarily have to be less accurate than an LCA in a later phase of the project. It is preferable to perform an LCA tailored to the data available (LOD) during the design process [32]. Nevertheless, the design parameters in the early stages of the design significantly influence the results [36, 25]. Schneider-Marin et al. [25] conducted a contribution and sensitivity analysis looking at the influence of the building's most influential parameters regarding uncertainty and vagueness. They found through the sensitivity analysis that the geometry and technical specifications cause the highest result uncertainty. Therefore, the design team can reduce result uncertainties greatly by reducing the vagueness of the geometry and technical specifications, like the amount of reinforcement, u-value, or thickness of components. Hollberg et al. [37] confirm this statement. They have found that early models are often not quality checked for LCA and overlapping materials can result in a volume difference of 40%, leading to very different results during the process from the final version. Architects are often unaware of the impact of the model on the accuracy of the LCA [25]. Making them aware of the issues of inaccuracy, or better, providing them with a user-friendly tool for the early-phase LCA model, could eliminate the obscurity of the model through more LCA-accurate modelling. Resch et al. [38] suggest adopting a Global Sensitivity Analysis (GSA) in building LCA modelling, which classifies the sensitivity of the model to changes in the parameters. They found that the applied time horizon, the carbon-storing capacity of materials and material-related technological progress are highly sensitive. Furthermore, the variation in the amount and type of data used in the LCA calculation is another limitation. Any systematic changes or updates to the database may significantly affect the interpretation of the results [39].

2.2.3 Introduction to Early-Phase LCA Calculation Tools

In the past, manual LCA calculations were often necessary, which can be very time-consuming. Whereas, today the integration process between BIM and LCA has increasingly important [32, 40]. The 3D model is rich in information and relatively easy to export to numerical data during the process. Therefore, it provides a good basis for process-integrated LCA, which requires as much detailed information as available at different stages [41]. Based on the literature review, it has been observed that the introduction of BIM-LCA integration methods is one important focus of current research. The BIM-LCA integration is expected to provide better compatibility and applicability of the comprehensive and valid LCA results [32]. Three different methods were adopted for the integration of BIM-LCA:

(1) The manual linking of the LCA database and the local BIM library. The LCA calculation takes place externally in an LCA software or Excel.
(2) Using Application Programming Interfaces (API) and different software can combine the LCA database and BIM data in a plugin. Alternatively, the BIM model data can get extracted as standard data (IFC and gbXML) to later get transferred to an LCA software to perform calculations.

(3) The required LCA parameters can be embedded in the BIM material library. Using BIM's parametric capabilities, visual programming, and BIM's graphical representation of the results, an LCA can be calculated, and the results presented in a comprehensible way.

In addition to BIM-based LCA calculations, there are also stand-alone LCA programs on the market. Some of them specialize in the early design phase. Others accompany the whole project and are designed for more detailed LCA. However, these programs often have an interface or plug-in option to BIM software. The following provides a brief insight into ATHENA Impact Estimator©, CAALA, Carbon Designer 3D by One Click LCA™, Reduzer AS and Tally®, as representative of possible calculation techniques.

ATHENA Impact Estimator©

The ATHENA Impact Estimator© (AIE) is a stand-alone, free online tool that allows designers to calculate the environmental impacts of building materials and systems early in the design phase without requiring a great degree of expertise. The software is based on the internationally recognized LCA methodology and can generate reports for LEED (Leadership in Energy and Environmental Design), Green Globe, and ILFI (International Living Future Institute) certification. LCAs for new buildings, renovations and additions can be flexibly evaluated to provide a detailed estimate of the carbon footprint. Users can additionally import energy simulation results to account for operational environmental impacts in addition to embodied effects. AIE is adjusted to regional aspects of North America, like the power grid, transportation modes and distances, and product manufacturing technologies, depending on the location of the building [42]. AIE is therefore widely used in the North American context [43]. AIE has been on the market since 2002 and is updated regularly (latest update February 2020).

In the beginning, the user describes the building assembly via dialogue boxes that request simple information such as span width and loads, building service life, and typology. Depending on their needs, users can add and edit materials flexibly, or import their material lists from any CAD application. AIE provides data on (1) GWP, (2) AP (Acidification Potential), (3) HH (Human Health) Particulate (4) ODP (Ozone Depletion Potential), (5) Smog Potential, and (6) EP (Eutrophication Potential) through the whole LC, from material manufacturing, including resource extraction, and recycling content, to related transportation, to on-site construction, to maintenance and replacement, to demolition and over to disposal. The software additionally shows energy and fossil fuel consumption. AIE allows comparing and contrasting the LC operation and embodied effects of different design options so that users better understand the consequences of their decision-making [42].

CAALA

The tool CAALA is based on Hollberg's doctoral thesis [44] written at the Bauhaus University in Weimar, Germany in 2016. It is a stand-alone web application but also offers a plugin option for Sketchup and Rhino. CAALA provides the user not only with LCA calculation but also generated LCC and energy calculations. The LCA evaluation is based on internationally recognized LCA methodology and the German certification systems BNK (Bewertungssystem Nachhaltiger Kleinwohnhausbau - evaluation system for sustainable small residential buildings) and DGNB of residential buildings, enabling the user to reach the certification systems' requirements. Furthermore, using the German database Ökobaudat and considering different climate regions in Germany, it is well suited for the German context [45].

In the beginning, a project is created. As a starting point, the climate region in Germany, the building type (single-family house, apartment building, non-residential, office building, retail, hotel), and the building assignment (new construction or renovation) are defined. In addition, it is selected whether the data set of Ökobaudat 2016 or 2020 is to be used, and the approximate project size is specified (GFA). For the cost calculation, CAALA also requires the input of the approximate duration of the construction phase. The project size and project duration can no longer be adjusted later in the process. In general, an LCA in CAALA is based on a 3D model that can either be created directly in Sketchup/Rhino or imported as a gbXML/IFC file. However, it is important to define the different building elements on the respective CAD layer so that CAALA can assign the surfaces to the building elements in the LCA calculation. Automatic recognition or parametric inference does not take place. Alternatively, the 3D model can be derived by a plug-in with Google Maps Street View, which converts an existing building into a basic surface volume of the envelope. The surface model can then be adjusted with the number of floors, the average floor height, and the window-to-wall ratio (WWR) on each façade. Additionally, the roof is assigned to either showcasing a roof or a ceiling to an unheated roof. The bottom floor is defined as floor-to-unheated space (basement), floor-to-ground, or ceiling (floor-to-heated space). This is required as CAALA also calculates the energy performance of the construction project. CAALA is structured in four steps. Step one, the 3D model creation/import, is followed by step two, in which parameters for materials, equipment technology and costs are defined. In step three, the data are analyzed and visualized. Not only the environmental impacts in terms of operation and embodied effects are shown, but also the energy performance and costs are calculated. The analysis is always done for all created variants. These can be compared to be able to make the project-corresponding decision in step four [45, 46].

Carbon Designer 3D by One Click LCA™

One Click LCA™ (OCL) is a standalone LCA calculation tool with a plug-in option for Autodesk® Revit® and Grasshopper. OCL always analyzes LCA in a cloud, although the software can adapt to material allocation practices and automatically updates the LCA calculation according to model changes [47]. The software is based on the internationally recognized LCA methodology and can generate reports for BREEAM, LEED, DGNB, and over 60 other certification systems. OCL provides LCA calculations for buildings, infrastructure projects, and products worldwide (Europe, North America, the Middle East, Asia-Pacific, and South Africa) throughout the whole LC according to the certification scheme approach. OCL has an integrated database that includes many of the EPD platforms globally available [48]. The tool is intended for use starting from LOD 200 [49]. For the early-phase design, where approximately LOD 100 is reached, OCL developed the add-on tool Carbon Designer 3D. This add-on allows quick LCA estimations without requiring much knowledge about the project. A baseline and variants with predefined building structures and different materiality can be created with the help of a parametric model to query design options. Carbon Designer 3D has been developed for the early design phase but it can also support detailed options and creation [50].

To begin, a new project needs to be created in Carbon Designer 3D. The project name, the type of reference building (according to national context), the estimated size (GFA), and the calculation period (service life) are required for input. Once the baseline is established, the user must select a building type out of office buildings, multi-family buildings, prisons, single-family homes, retail stores, hotels, cultural buildings, hospitals, and many other options. Step three is to define the scope of the screening LCA. Here, the building components to be considered (foundation, floor slab, structure, envelope, finishes, services) are selected or deselected, the number of above-ground floors, and the number of below-ground heated and unheated floors are defined, and the building structure is determined. The last step is the calculation of the geometry. To do this, the user must enter information about the height, width and depth of the building, the floor height, the maximum column spacing, the percentage of interior load-bearing walls, the number of staircases, the thickness of the floors and the building envelope, and information about the roof shape. Alternatively, Carbon Designer 3D uses default values according to the selected number of floors above and below ground as well as the GFA. Carbon Designer 3D then parametrically calculates the area of the building components, which serves as input parameters for the screening LCA. The automatically generated areas can be manually modified by the user if needed. Once the geometry is specified and submitted, Carbon Designer 3D calculates the estimated carbon footprint in tons of CO_2-eq. Results are presented either by element, by material or by classification. Building elements and single materials within an assembly of the base project according to the reference building can then get adjusted to different design choices. The resulting baseline project can be copied for further design exploration. Changes in the geometry require creating a completely new design as the structures need to get recalculated based on the new information. A graphical visualization displays the approximate building design including the carbon footprint of each building part in a 3D model. Carbon footprint results of up to four designs, either as copied baseline designs with different material options or as new designs with a different geometry, can be combined in one graphical output for better comparison. Different design options can thus be compared easily [50]. The chosen design option can then be saved to the project for continuing with the simplified LCA.

Reduzer AS

Reduzer is a new stand-alone LCA software developed as part of a dissertation by Resch [51] at the Norwegian University of Science and Technology (NTNU) and funded by the Norwegian Research Council. Lately, the tool has been released from the testing phase for better adaptation to the product market. In collaboration with industry players and through user testing, the software is now available for the first customers. Reduzer is a tool that allows construction industry professionals to easily calculate the environmental impact of a building, a neighborhood, or an infrastructure project. It supports emissions-based decision-making throughout the design process by combining environmental data, goals, and certification schemes in a cloud-based calculation workspace [52].

At the beginning of a project, the system boundaries and calculation methods are selected, and benchmarks are defined. This can be done either by selecting a scheme that specifies a combination of all three above or can be compiled individually and saved as a custom scheme. The available schemes are currently tailored to the Norwegian market and include NS 3720, BREEAM-NOR v6.0, FutureBuilt Zero and TEK 17 (2022). The initially selected scheme can get modified during the process, for instance, to be able to check how the project performs regarding other certification systems. Once the project has been set up, versions get added, copied, and customized. Different versions of a project can thus be compared and evaluated. A version is defined by specifying the geometry, building elements (a group of materials that compose a building part), and products (a single material). Together, they create the LCI. The geometry can either be generated via a so-called Automodel, which creates a simplified geometry of stacked cubes through parametric modelling. Alternatively, it can be generated through manual entries, or imported via Excel or BIM/IFC models. The respective products and components can be selected from an internal material library, with the option of checking and adjusting the comparability of information about transport distance and waste generation to the user’s project manually. Nevertheless, the library can be extended individually if specific products with their EPDs are used. Additionally, Reduzer offers reference buildings as a template, from which components can be transferred to the user's project in early-phases to calculate estimations of the environmental impact of the construction project. Not only does the link to reference buildings show Reduzer’s suitability for processes-accompanying life cycle assessment it also does by functions such as the possibility to switch between geometry entries. For example, at the beginning of the project, the model can be generated with Automodel. Later, a BIM model can be linked that provides more accurate in-process information and at the end, the exact built quantities can be entered manually to calculate a detailed LCA if needed. Moreover, Reduzer has announced to soon offer a tool that can suggest improvement measures to reduce the environmental impact of the design automatically. Reduzer offers reports, graphs, and diagrams showcasing the LCA results regarding GWP and costs throughout the whole LC [53].

Tally®

Tally® is an Autodesk® Revit® plug-in that allows designers to identify and quantify the environmental impact of construction methods and materials during the design process and generate reports for LEED, Green Globe, and ILFI certification. It not only calculates a life cycle assessment using the internationally recognized LCA methodology but also suggests more environmentally friendly material alternatives. Building elements in a BIM model are directly linked to building materials from the Tally® database. On request, Tally® provides the user with the LCA results either for the entire building or as a comparative analysis of different Revit design options during the process. Once materials have been assigned to components, a report summarizes the environmental impact of the project, including GWP, AP, EP, ODP, and smog formation potential as indicators, in addition to primary energy demand, non-renewable energy demand, and renewable energy demand. The results can be presented as total environmental impact or by LC level, Revit category, or CSI (Construction Specification Institute) division [47, 54].

2.2.4 Comparison of Early-Phase LCA Calculation Tools

Herrero-Garcia [55] conducted a comparison of available tools. She states that the choice of tool should be dependent on what the user tries to accomplish, how much knowledge about BIM and LCA the practitioners have, and at what stage of design the tool is intended to be used. Things like technical level, accuracy, efficiency, and quality are therefore decisive parameters of decision-making. She also recommends doing a quality check of BOM imports from CAD applications to limit errors of missing elements or multi-counting of elements.

Table 3 has been developed for this thesis and provides a comparison between ATHENA Impact Estimator©, CAALA, Carbon Designer 3D by One Click LCA™, Reduzer AS and Tally®. The green tools offer a parametric model generation for the early-phase specifically and are therefore the only ones qualified for later case study testing in this thesis.

Table 3 Comparison of different early-phase LCA calculation tools (green tools offer parametric model generation)

Location	Database	Indicators	LC-phases	Modelling	Application	System boundary	Computation	Tool
North America	own database	GWP, AP ODP, EP, smog, HH particulate, energy	A-C	manual entries, CSV, XML, Excel import	application	embodied effects (import of operational energy use possible)	LCA	ATHENA Impact Estimator©
Germany	Ökobaudat 2016 & 2020	GWP, AP, ODP, EP, PERT, PENRT, POCP, costs and energy	A1-A3 B4., B6 C3-C4 D1, D2	import gbCML, import IFC, 3D model from map (Street view)	web application, plug-in Sketchup and Rhino	embodied and operational effects	LCA, LCC, energy calculations	CAALA
global	own library including different databases	GWP	according to scheme	parametric	web application	embodied effects (import of operational energy use possible)	LCA	Carbon Designer 3D by One Click LCA
Norway, global	own library including different databases, manual entries possible	GWP, costs	according to scheme	parametric, direct BIM, import BIM, import Excel, manual entries	web application	embodied effects (import of operational energy use possible)	LCA	Reduzer AS
North A., global	own library including GaBi 2018	GWP, AP, EP, POCP, smog, energy	A-C	direct BIM	Revit® plug-in	embodied effects (import of operational energy use possible)	LCA	Tally®

Source: Own representation derived from respective tools [42, 45, 50, 53, 54]

2.2.5 Review of Early-Phase LCA Calculation Tools

The integration approach of BIM-LCA is currently primarily static, and BIM uses a fixed database. The mapping of the design process in BIM-LCA integration is therefore still limited [32, 37], which indicates that interoperability is not yet fully developed.

AIE is a simple but slow tool that allows users to manually add the BOM and assign standard material assemblies to the building parts. It is also possible in AIE to import a BOM from the CAD model, which will reduce errors, effort, and time [55]. Jrade and Jalaei [56, 43] used AIE in their studies on the integration of BIM in the design phase for sustainable building design. They note that AIE is a user-friendly tool that provides tables and graphs as quick results. According to Jalaei and Jrade, these results provide a reasonable overview of the environmental impact of the design. However, Basbagill et al. [6] state that the tool does not provide a sensitivity analysis that would show how environmental impacts would change over a range of design alternatives. They also claim that BIM has not been integrated efficiently, limiting the usefulness of AIE in the early design phase. Nonetheless, BIM use is scarce in early design in the field, so far as creating various design options is unpractical due to the complexity of BIM models [57]. Herrero-Garcia [55] also mentions that AIE's material library does not provide local and project-specific EPD data. Manual modifications about transportation, localization, or service life of the materials cannot be specified.

According to Santos et al. [58], Tally offers an advanced integration to the BIM environment, as it easily creates a BOM. However, the mapping of materials does not function automatically in Revit® but the user must correspond Revit's and Tally's material libraries. Additionally, the user cannot add materials to Tally's database, which is limited, though project-specific information about transportation and service life are adjustable.

OCL and Reduzer have extensive databases. In Reduzer, users can even easily add materials to a personal library. Additionally, project-specific information about location, transportation, and service life can be modified for each material in both OCL and Reduzer. Considering the correctness of the results, it must be mentioned, that OCL and Reduzer have been officially approved as an LCA calculation tool for BREEAM certification and OCL has been awarded a 100 % quality score [59]. Looking at the output results of OCL and Tally in comparison, Dalla Mora et al. [47] found, that values for GWP have an approximate difference of 10 % resulting from the use of different databases, including the different environmental impact of materials (about 22 % difference on average).

Therefore, there needs to be awareness from the user regarding database content and the availability of modification/addition of values to the database.

Method (1) (see chapter 2.2.3), the manual mapping of data like in AIE, has the lowest level of automation, and therefore requires more expertise and time, although the end-user has full control over processes and parameters during the LC [60]. As this thesis is intended to investigate and improve upon an early-phase LCA model for the use of all stakeholders, and AIE is not well suited for LCA-unexperienced users, AIE will not be examined closer. Soust-Verdaguer et al. [60] found, that the LOD 300 for environmental impact assessment is best suited for method (2), using API, in the early design phases. This already corresponds to a high level of detail that can only be achieved later in the design process. Likewise, Berg previously found in his 2014 dissertation [61], through the use of the tools IMPACT and Tally, that the creation of a detailed model is too time-intensive. Additionally, the design process is already too advanced at this point to make changes to the design that will effectively reduce the environmental impact. It is therefore expected that the use of Tally®, as well as CAALA and OCL as BIM plug-ins, are not suited for the early-phase but rather later in the process. Accordingly, Tally is also not discussed further in this thesis. Hollberg et al. [37] applied method (3), the integration of LCA data in the BIM library, to a real case study and found that automatic computation leads to incorrect results in the current design process. There are three possible solutions to solve the issue of early-phase LCA according to Hollberg et al. [37]:

(i) Adapting the design workflow by using predefined components with existing LCA calculations (e.g., through learnings from reference buildings). Holberg et al. add, that the limitation of the approach in terms of design freedom for innovative projects or architectural competitions is certainly given. However, this approach could be suitable for industrialized construction projects.

(ii) Using a simplified approach that is based on calculating embodied environmental impacts based on e.g., surface areas instead of volumetric models. This approach has proven to be beneficial in early design phases but is less accurate for as-built model certification.

(iii) LCA tools utilize findings from previous projects (machine learning) and automatically use typical assumptions for placeholder materials in early design phases.

CAALA applies approach (ii) by creating simple surface volumes from existing Google Maps Street View structures. By using Google Streetview rather than BIM, is limited to existing building geometries and does not allow a simple early-phase LCA calculation in combination with a free design process. CAALA with Sketchup or Rhino can only include the building elements that are represented in the model in the calculation. An empirical assumption of missing elements in the early-phase, such as the interior walls, does not take place. Carbon Designer 3D by OCL and Automodel by Reduzer create their simplified model and apply components from reference buildings to the early design phase. Materials can be manually specified and modified afterwards. Since this thesis focuses on the creation of a parametric model (including more building elements as displayed in the model), subsequent chapters will focus to a greater extent on Reduzer, and Carbon Designer 3D.

To summarize, the following qualities are identified to be important for an early-phase LCA calculation tool in this chapter: (1a) The ability to calculate highly simplified models and (1b) the generation of a simplified model; (2) large databases with accessibility and editability by the user; (3) predefined components with materials mapped onto reference buildings; (4) sensitivity information about results; (5) continuity of the model in next phases.

2.3 Decisive Parameters of an Early-Phase LCA Model

Based on the literature review and the evaluation of Reduzer and Carbon Designer 3D's parametric early-phase models, four main research areas for the development of an early-phase LCA model were identified. The four main research areas are **(1) General Building Information**, an area that defines the basic geometry, basic building information, and scope of the early-phase LCA; **(2) Building Structure**, an area that involves identifying the critical building elements for the early-phase LCA BOM; (**3) Material and Product Information**, this identifies which material data, reference, or sample components can be used in the early-phase of LCA; and **(4) Parametric Modelling**, which describes the parametric relationship between basic geometry information and building component quantities. This chapter provides an overview of the findings of the literature review and the review of the aforementioned early-phase LCA tools.

2.3.1 General Building Information

As a starting point for an LCA, the scope of the calculation must be specified. This includes a project description and general information about the spatial system boundaries and the included LC phases. Meanwhile, several building certifications and guidelines exist, defining a calculation scheme for an LCA, and thus the spatial system boundaries and LC phases included. Therefore, it should be determined right at the beginning which LCA approach to follow. The LCA-related input data (project description, spatial system boundary, LC phases, calculation scheme) are also necessary for more detailed LCA calculations and are therefore not the focus of this work.

Subsequently, the basic geometry and a functional equivalent must be defined as a base for further calculations. The functional equivalent, according to EN 15978:2011, is defined by the building type (office, residential, etc.), the relevant technical and functional requirements (e.g., national regulations, customer preferences), the use pattern (e.g., occupancy, usable floor area), and the service life [14]. That basic information about the building is relevant for the early-phase building geometry and further derivations by functional equivalents. Only when buildings have a common identity, can empirical data be used as assumptions for missing data at an early stage, and LCA results are comparable. The two exemplary tools Reduzer and Carbon Designer 3D use approaches to describe a functional equivalent, are shown in **Table 4**. The service life and type of use must be defined in both tools. Regarding the materiality of the design, Reduzer asks that the user chooses a template of a reference building that best describes the material approach of the design. Carbon Designer 3D asks for the superstructure, i.e., the type of material for the structural system to best categorize the building materiality. Regional conditions are also defined differently in the tools. In Reduzer, the user-chosen calculation scheme defines a national calculation context. In addition, the location of the construction site needs to be specified. Carbon Designer 3D, on the other hand, offers a choice of reference buildings with a national context to define the corresponding building standard. When defining the basic geometry, both programs work slightly differently. Automodel and Carbon Designer 3D distinguish between above-ground and below-ground floors. In addition to the number of floors above and below ground, the GFA is also required. Automodel provides a simplified information entry for the user by providing the option to enter the building's footprint or length and width, which saves the user time converting between values. Using the values entered up to this point, the programs automatically populate all other required values using default values, and initial LCA estimates can be made on the design. However, the geometry can be specified if more information is already available in the design process. The parameters in

Table 4 under "specification of geometry", automatically generated by the applications, can thus be individually overwritten.

Table 4 Comparison of required input parameters for basic building information of the early-phase LCA calculation tools Automodel by Reduzer and Carbon Designer 3D by OCL (own representation)

<table>
<tr><th></th><th colspan="3">Automodel by Reduzer</th><th>Carbon Designer 3D by OCL</th></tr>
<tr><td>LCA input</td><td colspan="3">calculation scheme
distance to waste handling</td><td>included components</td></tr>
<tr><td rowspan="4">functional equivalent</td><td colspan="3">service life incl. in the scheme</td><td>service life</td></tr>
<tr><td colspan="3">type of use</td><td>type of use</td></tr>
<tr><td colspan="3">template of a reference building</td><td>superstructure</td></tr>
<tr><td colspan="3">location</td><td>location of a reference building</td></tr>
<tr><td rowspan="6">basic geometry</td><td colspan="2">number of stories above ground</td><td rowspan="3">GFA</td><td>GFA</td></tr>
<tr><td>width</td><td rowspan="2">footprint</td><td rowspan="2">stories above ground</td></tr>
<tr><td>depth</td></tr>
<tr><td colspan="2">number of stories below ground</td><td rowspan="3">GFA</td><td>stories underground heated</td></tr>
<tr><td>with</td><td rowspan="2">footprint</td><td rowspan="2">stories underground not heated</td></tr>
<tr><td>depth</td></tr>
<tr><td rowspan="7">specification of geometry</td><td colspan="3"></td><td>height above ground of build.
width of building
depth of building</td></tr>
<tr><td colspan="3">WWR total
story height
external door
wall thickness
average room size</td><td>internal floor height

internal GFA</td></tr>
<tr><td colspan="3">roof (flat/gabled/shed)
roof terrace (y/n)
roof thickness
roof skirt length</td><td>roof shape efficient factor</td></tr>
<tr><td colspan="3">slab thickness</td><td>slab thickness</td></tr>
<tr><td colspan="3">% outer wall area load bearing
% inner wall area load bearing</td><td>maximal column spacing
% load bearing internal walls</td></tr>
<tr><td colspan="3">foundation slab thickness
ground conditions (depth to solid ground)</td><td>secant piling wall (y/n)
soil stabilization (y/n)</td></tr>
<tr><td colspan="3"></td><td>number of staircases</td></tr>
</table>

WWR = Window to Wall ratio; (y/n) = yes or no activation; GFA = gross floor area

2.3.2 Building Structure for Early-Phase LCA

To better understand the building structure for cost estimation purposes, energy calculations, or LCA data structures, national standards and guidelines have been developed in various countries to decompose buildings into systematically and hierarchically located building parts. Soust-Verdaguer et al. [30] conducted a comparative analysis of national standards and guidelines from Austria, Belgium, Brazil, Canada, the Czech Republic, France, Germany, the Netherlands, New Zealand, Spain, Switzerland, and the UK. They found that most of the national standards divide the building into six different hierarchical levels (level 0 – level 6), whereas levels 1 to 3 describe the structure of the building, and levels 4 to 6 describe the building's elemental classification, the latter mainly depending on the building characteristics and granularity of the building model. The resulting hierarchical decomposition defines a building (level 0, consisting of e.g., the building, HVAC installations, electrical power, telecommunication and automation, other installations, outdoors) in building systems (level 1, e.g., ground and foundations, load-bearing systems, external walls, etc.) with their building parts (level 2, e.g., primary structure, roofing, system ceiling, etc.), composed of different building type elements (level 3), building elements (level 4), sub-elements (level 5), and materials (level 6). The decomposition of buildings differs according to national approaches. Soust-Verdaguer et al. studied the impact on LCA results of the heterogeneous models on a reference building and concluded that the LCI, LCA database and communication of results differ by approach. Also, the more detailed and hierarchical the LCI is organized, the easier it is to identify building parts, elements, etc. in the results and, therefore, to optimize them. However, the building structure then also becomes highly complex and may not be suitable for the early-phase, where little information is available [30]. In the early-phase, the primary goal is to minimize the environmental impact. Strict compliance with a national standard and the associated building decomposition is therefore not yet necessary. Rather, it is important to break down the building structure into a model that is as simple as possible but still has LCA significance. The theory is that the earlier in the design process, the lower the definition of the hierarchical level. If the design process is more advanced, more precise definitions (higher level) can be given [30, 31]. However, Resch noted in his dissertation that unknown building parts should be included through empirical estimation to get a complete picture of the building's LCA. The more parts that are included, the more accurate the early-phase LCA estimate, according to Resch. Moreover, the inclusion of more building parts in the early-phase should not be a problem of a lack of information but rather requires a technical solution to fill the information gap with empirical data [51].

The contribution analysis identifies where the biggest potential for emission and energy reduction lies. It, therefore, reveals the building parts contributing most to a specific indicator like GWP and can guide architects to better decision-making regarding environmental friendliness. Schneider-Marin et al. [25] state that contribution analysis works for homogeneous building parts, so overall decisions about e.g., structural material can be derived. Thus, building parts which are differently assembled, like internal walls or finishes, can skew results. Including more building part categories could result, however, in a too-complex LCA model for the early-phase.

Table 5 Critical building elements regarding embodied emissions/GWP according to literature (own representation)

	Resch et al. [62]	**Schneider-Marin et al.** [25]	**Design2Eco** [63]	**EeBGuide** [28] **& Meex et al.** [27]
common strategic parameters	primary construction	structure	structure	structure
	outer walls	Insulation	façade	exterior walls
	outer roofs		roof	roofs
	glass roof, roof hatches			
	windows and doors	windows	windows	windows
specific findings		internal	interior	interior
			slabs	slabs
			foundation	foundation
				finishes
	stairs and balconies			
	PV		(MEP)	

With the help of a literature review, decisive building elements were identified. **Table 5** shows the building elements that are critical in terms of embodied emissions or GWP according to case studies of the literature cited. However, it is not always clear where the boundaries between building elements and materials lie. The overview therefore only provides a list of the elements mentioned.

Resch et al. decomposed the building according to the Norwegian standard NS 3145:2022. For simplification, they reduced the scope to the 0^{th} to 3^{rd} level. This resulted in the 1^{st} level including the 'envelope, foundation, and structure' causing the majority of embodied emissions, the 'electric power' causing about one-quarter of embodied emissions, and ‘heating, ventilation, and sanitary’ with the lowest embodied emissions. Looking at the 2nd hierarchical level, Resch found, that ‘**outer walls**’, ‘**outer roof**’, and ‘**stairs and balconies**’ are the relevant building elements of the main building construction to focus on. Mainly all embodied emissions of ‘electrical power’ are caused by ‘**PV**’, resulting from a high production emission factor and production replacement factor, as the service life of PV is short. In Resch's study, the data contained little environmental information on the building elements "heating, ventilation and plumbing," so they were not particularly relevant to embodied emissions. However, more recent studies show that technical installations are estimated in about 20 % of the total GHG emissions of new buildings and 40 % of renovations [64]. The 3rd level shows the sub-elements of the building parts. Here, ‘**windows and doors**’ are the main drivers for embodied emissions for ‘outer walls’, followed by the ‘**primary construction**’. ‘**Glass roof, roof hatches**’ are the main contributors to embodied emissions of ‘outer roof’ [62].

Schneider-Marin et al. considered building parts typically containing the greatest share of building materials, including ‘**structure**’, ‘**windows**’, ‘**internal**’, and ‘**insulation**’. They did not consider a national decomposition standard but focused rather on the LCA significance of the building (sub-)elements. The contribution analysis shows that the structure is the largest contributor, responsible for about half of the total GWP, followed by ‘windows’, then ‘internal’ and lastly ‘insulation’. The choice of structural material is therefore decisive, and the use of wood can e.g., reduce GWP by about 25 % according to Schneider-Marin. Optimizing one building element will result in a different distribution of GWP, meaning, lowering e.g., structural embodied emissions will lower its total contribution of GWP, resulting in a higher significance of the second largest contributor of GWP [25].

According to the Design2Eco final report, presenting a strategic plan for LCC and LCA for office construction projects at an early stage, in the five sample projects, the structure accounts for about 36 % of the total GWP on average; followed by MEP 19 %; interiors 19 %; roof, base: insulation 9 %; windows and doors 8 %; ext. walls: façade, insulation 7 %; and others 3 %. [63, p. 106] The **structure** seems to be the strategic parameter at an early stage to significantly reduce GWP through material selection and structural systems. The report also mentions that the **slabs** are a significant contributor to the structure, resulting in more slabs leading to significantly higher GWP. However, a fewer number of slabs increases the influence of the **foundation** and **roof**. According to the report, the effect of MEP cannot be quantified conclusively, but it has a large influence on operational impacts and is consequently not as relevant for embodied emissions. The **interiors** are responsible for the second largest environmental weight, which is due to the high replacement rate and maintenance needs. The influence of the windows and doors is notable, but negligible according to the Design2Eco report. The **window areas** and thus the environmental impacts increase with an increasing number of floors. The choice of the **frame material** has a great influence on the environmental impact and is the strategic parameter for GWP reduction for windows. In addition, the report mentions the impact of **façades**, which have a greater impact on buildings with more than five stories. However, depending on the choice of materials, façade cladding can noticeably increase the overall GWP value [63].

According to the EeBGuide, screening LCA should cover the building envelope, including **exterior walls**, **windows**, **roofs**, and **floor slabs**, as well as the **load-bearing structure** [28]. These elements are responsible for about 76 % of the embodied emissions on average according to El Khouli et al. [65]. For simplified LCA, the EeBGuide recommends adding a foundation, interior walls, building services, and finishes. Meex et al. already discussed the EeBGuide differentiation and concludes, that *"adding components during later stages of [the] design process causes an increase in environmental impact [...]. Furthermore, the results from screening and simplified LCA cannot be compared due to different system boundaries."* [27] Therefore, it is advisable to include approximately the same building elements in the early-phase as in the later stages of the process.

2.3.3 Material and Product Information

Compiling an LCA requires not only the BOM but also the associated product or material data with their respective environmental influences. However, at an early design stage, manufacturer-specific products have not yet been chosen for the project. According to Meex et al., the input parameters should be limited and chosen consistently throughout the design phases. Libraries with standard materials or building components e.g., national averages on common practice, can fill the knowledge gap, to provide default values on missing data for materials in buildings [27]. The EeBGuide recommends the use of average data in the early design phase as the focus is on design development and not on specific product selection. Rather, general material decisions and associated building structures must be addressed. Further, it states that the product stage (A1-A3) has the largest share of embodied emissions and must therefore be included. EeBGuide also recommends including the operational use of energy and water (B6 and B7) in a screening LCA [28], as A1-A3 and B6 together account for 70 – 90 % of the total environmental influence of residential buildings [27, 65]. According to Ganter et al., average product data or specific product data can replace the generic data later in the process (see **Figure 10**). Generic data were compiled using publicly available statistics and literature. They are not verified but are subject to a database (e.g., Ökobaudat, GaBi, etc.) internal quality check. They represent worst-case estimates and include a safety margin of 10 – 30 % for all production phases. In contrast to generic data, EPDs are based on direct manufacturer information, which must, however, be verified and certified by an external institution. They can either be product specific or an average value, coming from a single plant or several plants. The following **Figure 10** provides an idealistic overview of the different data approaches and their use during the design process according to Ganter et al. [66].

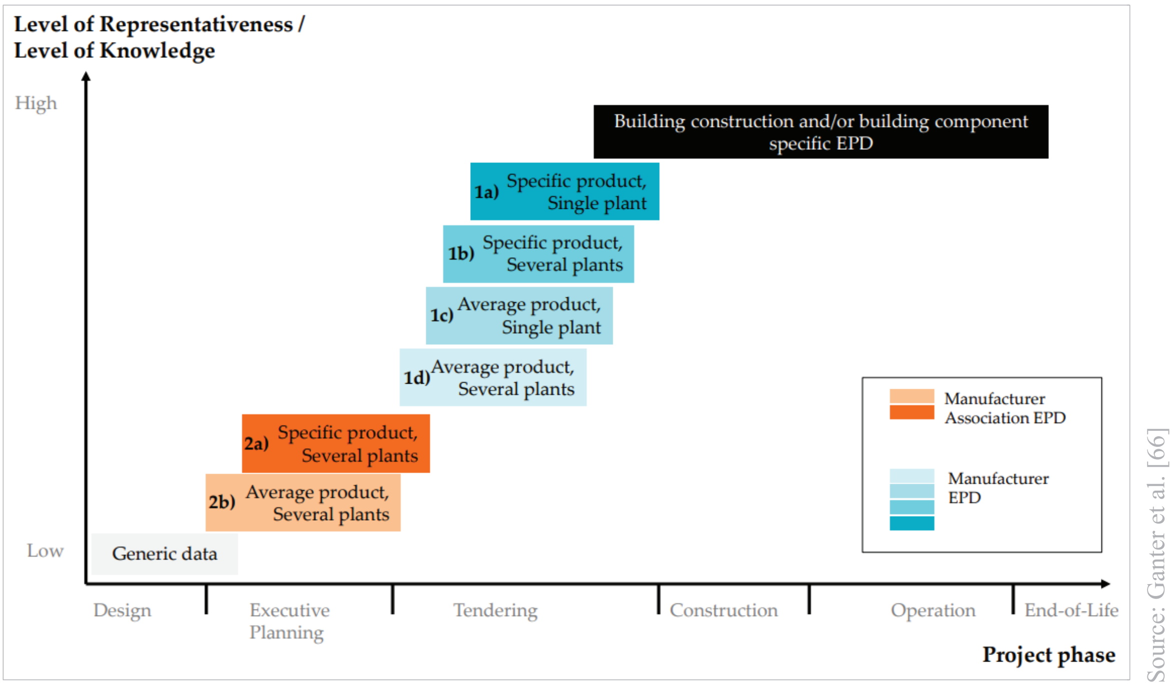


Figure 10 Overview of possible EPD data types and their application for LCA purposes in different project phases

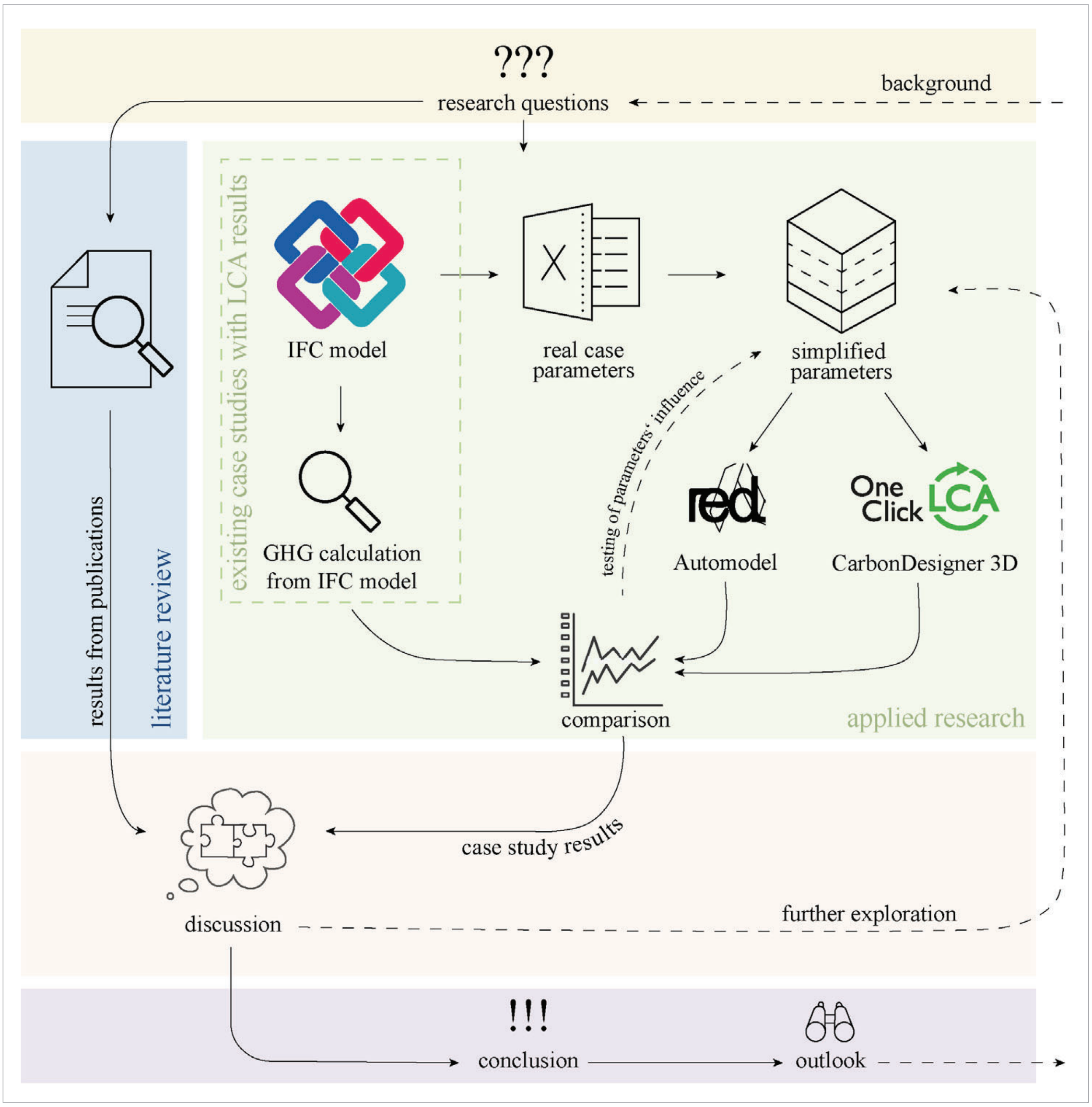
Nonetheless, the application of datasets requires defined component assemblies. However, the specific assembly of components is not yet defined in the early design phase. Rather, fundamental decisions are to be made, such as whether to build with wood or concrete. In the meantime, several guidebooks and visualization methods have been published, such as the Gronn Materialguide [67], or the Construction Material Pyramid of CINARK (Center for Industrialized Architecture) [68] which considers the environmental impact of single building materials to help inform architects more easily. However, singling out individual materials and comparing them without a structural context to derive LCA decisions is questionable. Different materials have different qualities. For example, they have different properties about acoustic insulation, fire protection, thermal insulation or load-bearing capacity and thus influence a multitude of assemblies. According to Saade et al, the outcome of an LCA study depends considerably on the decisions and scenarios made when modelling the LC of the building. When applying LCA to a complex system such as a building, the number of questions to be addressed increases, and rules of thumb become less meaningful and less truthful [69]. It is therefore important to look at the whole system and to conduct a screening LCA, including a simplification of geometry and input data with corresponding building elements. Reduzer uses reference buildings as templates to assign materials with EPDs and assembly information to the components [53], Carbon Designer 3D applies data from its library according to the structural material chosen by the user [50].

2.3.4 Parametric Modelling

Parametric modelling implies the use of parameters to define a shape. It is about the use of geometrical relations [70]. The parametric modelling method allows designers to create models such that by changing a few parameters, the whole model automatically adapts according to the pre-defined relations, meaning, the intended design is captured [71]. For example. Meex et al. recommend, using e.g., default values for the amount of m² per GFA of e.g., interior walls to limit the modelling effort but still include important building elements [27]. This approach is followed by the early-phase LCA calculation tools of Reduzer's Automodel and OCL's Carbon Designer 3D.

3 Methodology

This chapter presents the methodology employed in this master's thesis. Building upon the insights gained from the comprehensive literature review and in-depth case study investigations, this research addresses the key research questions it seeks to answer.



Source: Own representation

Figure 11 Methodology of this thesis

3.1 Literature Review

The literature review describes systematically the collected previous research and gives an overview of current findings. It represents a foundation for advancing knowledge and facilitating theory development. It also addresses the research questions of this thesis [72]. The initial strategy was to find answers to the key question: "Why is it important to consider embodied emissions in the construction sector" by searching current publications from research bodies like the IPCC, UN, or EU Commission and snowballing their cited literature. Further definitions, current practices, and findings from the latest research regarding early-phase LCA were found through systematic research in articles of scientific journals, books, and guidelines; searching through keywords like 'BIM LCA integration', 'early-phase LCA for buildings', 'building structure and LCA', 'ZEB definition', 'uncertainty in early-phase building LCA', 'building LCA calculation tools', 'parametric modelling', 'building design process', 'parametric building LCA calculation', 'simplification of building LCA', and 'dynamic building LCA' and reviewing their sources. Based on existing publications, previously researched topics could then be summarized in the preceding chapters. In doing so, the focus was on bundling current publications in a topic-specific manner and in turn, concluding different early-phase LCA tools, and the decisive parameters of an early-phase LCA tool. The latter topic provides the answer to the research question *Q1* of this master thesis and was divided into four areas. (a) general building information, (b) building structure, (c) material and product information, and (d) parametric modelling. In each area, a comparative analysis was conducted with different sources and different existing early-phase LCA tools to create a broad and holistic picture of current findings. Subsequently, the case study analysis can be used to verify the statements made in the literature review and to relate the case study results to previously conducted studies.

3.2 Applied Research

In this master thesis, two case studies were investigated to answer the research questions. The *Vollsveien* project represents an office building in Oslo, and the second (anonymized) represents a common Norwegian single-dwelling house, referred to in this thesis as *Norwegian Single-Dwelling*. The case study investigations are based on the IFC models and the LCA calculations of the final designs provided by Reduzer AS. To identify important parameters of the projects, the results of the LCA of the final design were analyzed early on in the research. For this purpose, a contribution study was carried out, considering the influence of the different building elements on the total GHG emissions. The case studies were hierarchically divided into building elements based on the NS 3145:2022 standard. Accordingly, information can be provided on the elements 'ground and foundation', 'columns and beams', 'exterior walls', 'interior walls', 'slabs', and 'roof'. Subsequently, the categories were analyzed in more detail and the respective proportions of 'structural elements', 'non-load-bearing elements', 'glass elements and doors', 'finishes' and 'ceiling system' of the respective building elements were determined.

Table 6 Parametrically created component list by Carbon Designer 3D by OCL and Automodel by Reduzer (own representation)

Carbon Designer 3D by OCL [50]		**Automodel by Reduzer** [53]	
foundation	foundation	ground and foundations	
	frost insulation	load-bearing	columns
	cleanliness layer		beams
ground slab		external walls	load bearing external walls
structure	floor slabs		non-load-bearing external wall
	columns		glass façade
	shear walls		windows, doors, and gates
	diagonal wind bracing		outer cladding and surfacing
	connecting parts		interior surfacing
	beams	internal walls	load-bearing internal walls
	secondary beams		non-load bearing internal walls
	load bearing internal walls		system walls, glass walls
	balconies		windows, doors, and gates
	staircases		cladding and surfacing
enclosure	underground wall	slabs	cantilevered slabs
	external walls		floor on ground
	cladding		raised floor, screeds
	windows		floor surface
	external doors		fixed ceilings, surface treatment
	roof slab		system ceilings
	roofs	roof	primary structure
finishes	internal walls		roofing
	floor finishes	stairs, balconies	internal stairs
	ceiling finishes		balconies and verandas
	internal wall finishes		

The parametric modelling approach for the model generation at an early-phase is followed in the programs Automodel by Reduzer and Carbon Designer 3D by One Click LCA. The tools ask the user to specify the simplified geometry at the beginning of the application. Other known parameters, such as the WWR or assembly thickness, can refine the simplified geometry. If further information is not available in the early design, the gaps are filled with default values. The custom values, together with the default values, allow the parametric modelling of a complete building model. In the next step, a component list (see **Table 6**) can be generated. For example, by specifying the building dimensions and the window-to-wall ratio, the façade area and the window area are calculated. The window area can then be subtracted from the façade to obtain the area (m^2) of the exterior wall parametrically. Therefore, with the help of the parametric approach, relationships between building components can be predefined to obtain sufficient information from the early-phase in order to calculate a complete LCA at an early-phase. The parametric relationships used by the two aforementioned applications are not transparent to the user but can be inferred by logical reasoning.

Based on the IFC model file and the quantities of the elements in the LCA calculation, areas such as GFA, number of floors, or floor height of the final design could be determined (see **Table 8** & **Table 9**). With this characteristic information as a baseline, simplified parameters were developed as input parameters for the early-phase being able to develop a parametric model with comparable area shares to the real case model. The simplified parameters were imported accordingly into the prediction tools, resulting in a six-sided cube as an output, consisting of a set of above-ground and below-ground floors. Comparability of the materials and input parameters used was explicitly considered, but without significantly affecting the program-specific assumptions. Accordingly, the goal was to maximize the use of default values with comparable input conditions. For example, the dimensions of the building were automatically derived by the tool using only GFA and height (number of stories and story height) as input parameters. Also, the area of interior walls had not been processed by the author but remained under parametric consideration by the tools. Furthermore, the results of the GHG estimation and the included building elements areas were analyzed and compared with the final emission calculation and the included areas of the building elements from the developed design. Further explorations on geometry, component selection, and parametric computation will be carried out subsequently. The studies can be categorized as follows:

Table 7 Categorization of early-phase LCA studies of this thesis

1 Basic Early-Phase LCA	Basic early-phase LCA with a general model input of GFA, height, number of stories, and typology for case studies 1 & 2
2 Geometry Study	Adjustment of the basic LCA by compliance with the proportions, hence of the envelope area. Consideration of the complexity of the design through separate modelling of different functional units.
3 Component Study	Adjustment of the number of interior walls to the actual quantity to study the influence of the distribution of construction types, quantity, and GWP/unit of internal walls.
4 Parametric Study	Investigation of the influence of the input parameter 'average room size' on the number of internal walls in Reduzer. Development of a method to calculate the number of internal walls.

3.2.1 Embodied Carbon Consideration Methodology

The term ‘embodied carbon’ here refers to GHG emissions of the associated building materials, measured as GWP in CO_2 equivalents. This simplification improves clarity but is not the same as GHG emissions or CO_2 equivalents, rather it is a practical term, that helps grasp the concept while acknowledging that the intricacies of embodied carbon differ from direct GHG emissions and their CO_2 equivalent measures.

The calculation method of the DGNB ENV1.1 Complete calculation method (International version 2020) was used, following the static approach without technological evolution consideration. The life cycle phases A1-A3, B4 and C3-C4 over a reference period of 50 years were included. Neither biogenic carbon uptake nor cement carbonation is considered in this method. Only the following elements of the building are taken into account in the calculation methodology: (1) External walls and basement walls, (2) roofs, (3) slabs, internal floors and ceilings, (4) ground slab, (5) foundation, (6) interior walls and (7) the load-bearing structure such as columns and beams. Elements such as stairs, balconies or heating and cooling systems, external installations, and other building installations or technical equipment were not included in the system boundary of the LCA calculation.

3.2.2 Case Studies

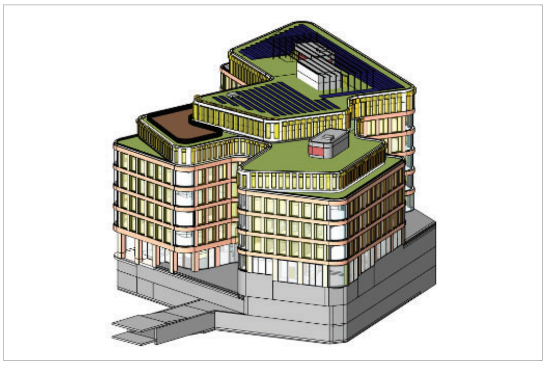
The two case studies used in this work are presented below. Case Study 1 is an office building with seven floors above ground and one below ground in Oslo. Case Study 2 is a two-story single-dwelling house without a basement, which is typical for the Norwegian context. The data was provided by Reduzer AS.

Case Study 1 – Vollsveien

The Vollsveien project by A-Lab architects is in the 150-year-old industrial district of Lilleakerbyen in Oslo, which is to be transformed into a vibrant and future-oriented neighborhood. An office building is planned at Vollsveien 9-11 as a pilot project to explore what it means to design a sustainable office building. Leading parameters in the design were the ability for disassembly and robust solutions to enable a long-lasting lifespan of over 120 years [73]. The project is an ambitious construction endeavor due to its focus on sustainability, its long-planned life span, and the reusability of all components. The solutions selected in this design may deviate strongly from standard practice in multiple cases.

Source: ©A-Lab architects [73]

Figure 12 Rendering of Vollsveien 9-11



Source: A-Lab architects

Figure 13 IFC-model of Vollsveien 9-11

Table 8 Characteristics of Vollsveien (own representation)

Stories above ground	7	**Stories below ground**	1
Story height above ground	1st floor 4,3 m 2nd to 7th floor 3,7 m	**Story height below ground**	3 m
GFA above ground	14,455 m²	**GFA below ground**	2240 m²
Footprint area	2065 m²	**Roof area**	2340 m²
External wall area	7245 m²	**Internal wall area**	22,845 m²
Ground slab area	2594 m²	**Slab area**	14,455 m²
Typology	office	**Structural material**	concrete

The building with a GFA of 16,695 m² distributed over eight stories was designed as a concrete structure, with the non-load-bearing walls built as steel stud walls. The façade is made of bricks and wooden cladding. A special feature of the project is the use of E-slabs, which are shaped like a wave. Due to their wave shape, an installation level for ventilation can be integrated into the crests and troughs of the waves, i.e., into the slab structure.

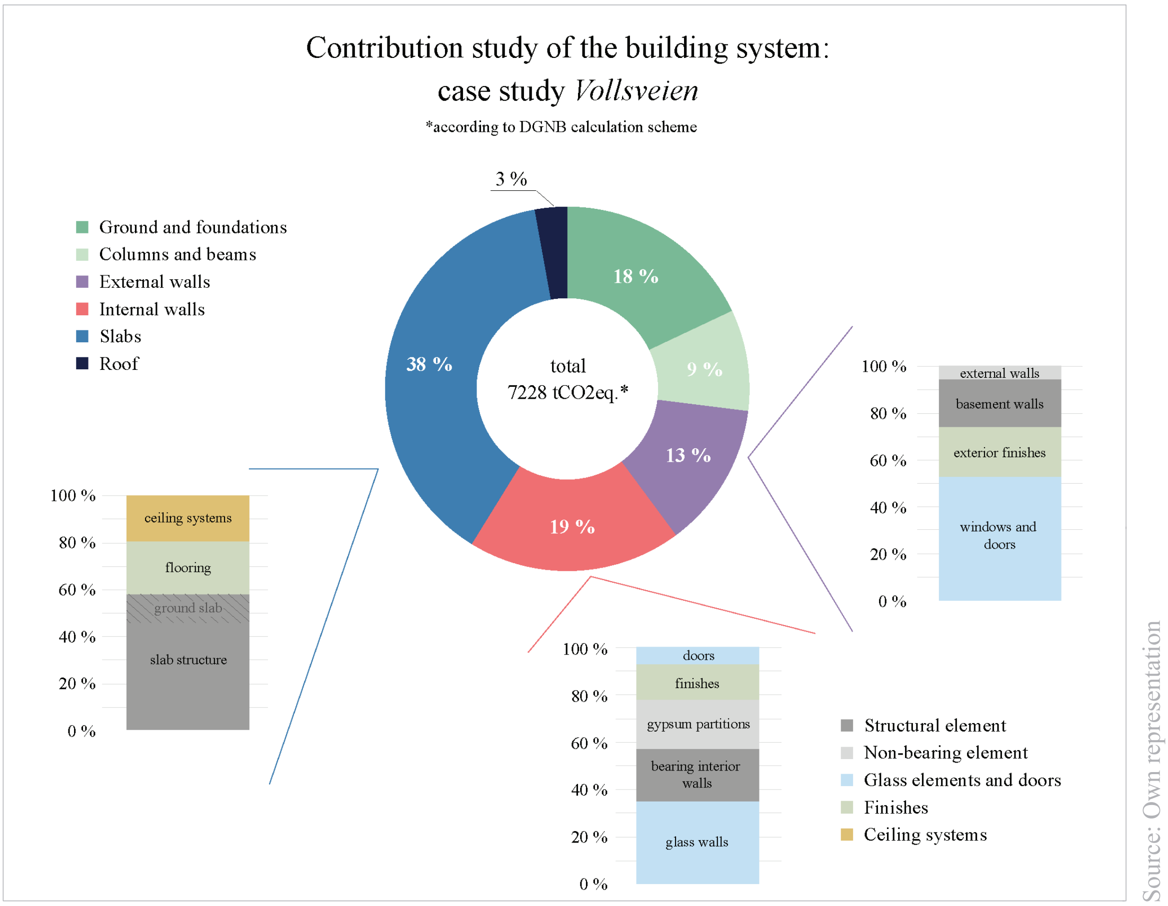


Figure 14 LCA results and contribution study of the final design of Vollsveien

The materials of the final design are responsible for **7228 tCO_2eq** in total, according to the DGNB International calculation scheme. The emissions are distributed as shown in **Figure 14**. Accordingly, the slabs are responsible for about 38 % of the total emissions, of which about half are caused by structural elements. The other half is the result of floor finishes and ceiling systems. Interior walls are the second largest emitter, with glass partition walls accounting for over one-third of the emissions, followed by internal load-bearing walls (22 %), plasterboard partition walls (21 %), finishes (15 %), and doors (7 %). In the third largest share are the emissions for ground and foundation with 18 %, followed by external wall emissions at 13 %. In the latter case, more than half of the emissions are caused by windows and doors. Columns and beams and the roof are responsible for 9 % and 3 % of total emissions, respectively.

Case Study 2 – Norwegian Single-Dwelling

A Norwegian prefabricated house manufacturer (who wishes to remain anonymous) offers different houses in a catalogue. *Norwegian Single-Dwelling* represents one variant of a common one-dwelling house in Norway.

Source: Anonymous

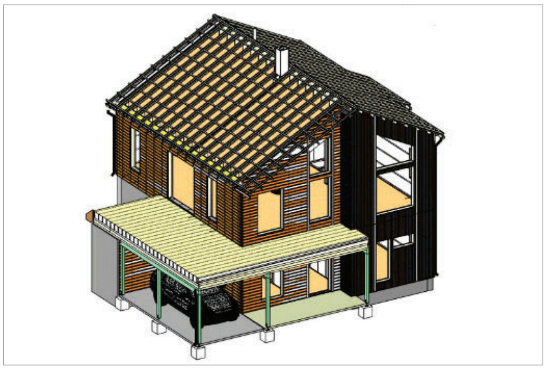
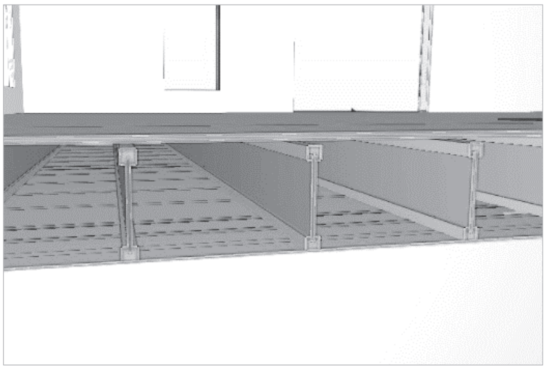


Figure 15 IFC-model of Norwegian Single-Dwelling



Source: Anonymous

Figure 16 Floor slab assembly of Norwegian Single-Dwelling

The building is planned in timber frame construction and consists of two stories above ground, without a basement. The GFA of the project, including two stories, an unheated storage room, and a carport, is 209 m². The heated main building (two stories without a storage room and carport) offers 156 m². A notable element is the slab structure (**Figure 16**) consisting of wooden I-beams, whose construction is particularly light and material-saving.

Table 9 Characteristics of Norwegian Single-Dwelling (own representation)

Stories above ground	2	**Stories below ground**	0
Story height	3 m	**Roof angle**	27°
GFA	209 m² / 156 m² without a carport	**Roof area**	115 m²
Ground slab area	84,3 m²	**Slab area**	80,3 m²
External wall area	281 m²	**Internal wall area**	127 m²
Typology	one-dwelling	**Structural material**	timber-frame

The final design's embodied emissions are **29,3 tCO_2eq** in total, according to the DGNB International calculation scheme. Contrary to the results of the office building from Case Study 1, the largest emitter is the exterior walls in this single-dwelling house with approximately 39 %. This is due to the high proportion of exterior walls touching the ground as a result of the hillside location of the building. The basement walls are responsible for about 45 % of the exterior wall emissions, followed by the windows and doors (28 %), exterior walls (19 %) and façade (9 %). The second largest contributors to GHG emissions are slabs at 31 %, primarily caused by the ground slab (43 %) and slab structure (24 %). The flooring accounts for almost all of the remaining emissions as ceiling finishes only account for 0.8 %. As expected, the roof is gaining importance due to the low number of stories and represents the third largest emitter with 14 %. Interior walls are responsible for about 11 % of emissions, followed by ground and foundation at 4.4 %. Columns and beams take a minor role with only 0.4 % of total emissions.

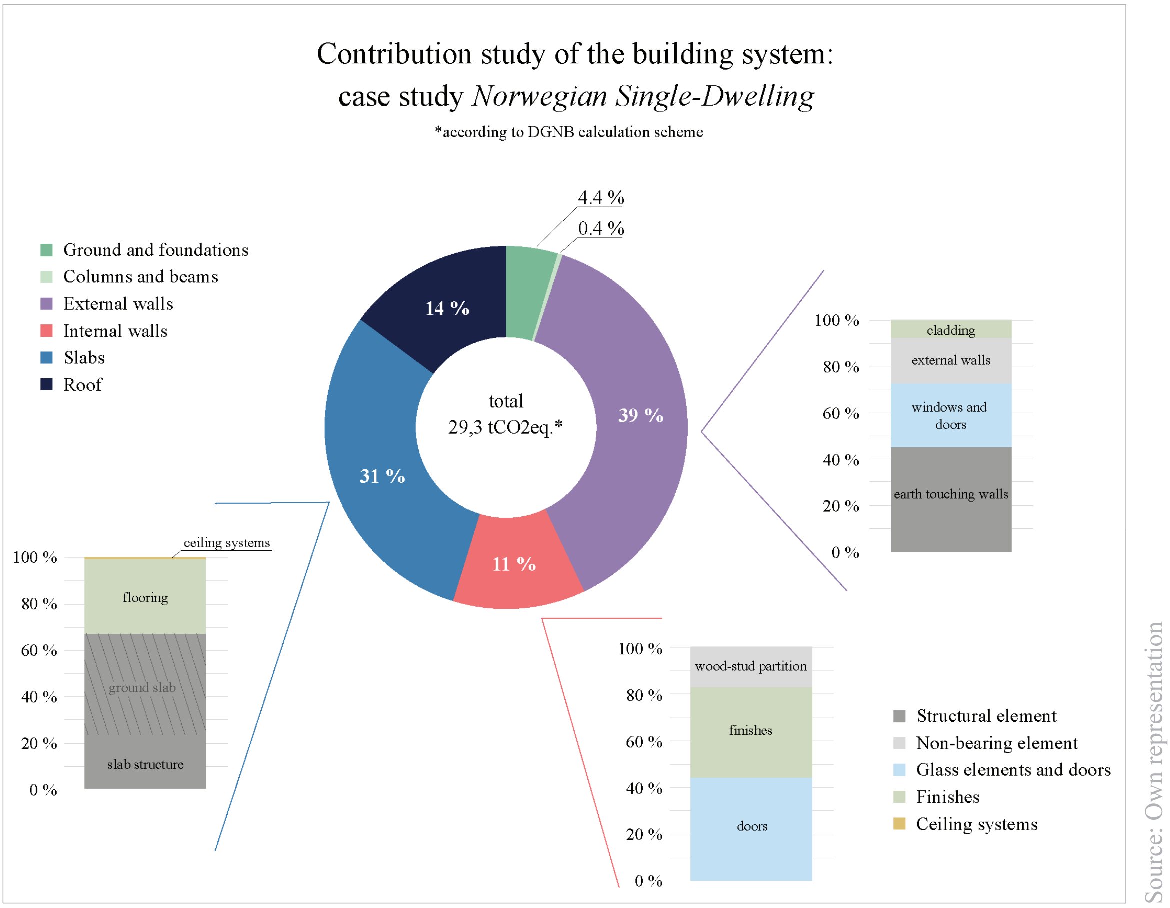


Figure 17 LCA results and contribution study of the final design of Norwegian Single-Dwelling

3.2.3 Geometry Study

To determine the required level of detail of the input model for the early-phase LCA, the geometry study investigates the influence of (a) the **proportions** of the model as well as (b) the **complexity** of the model.

(a) For the proportion study, the depth and width of the design are derived from the exterior wall area, footprint, and height of the real case design. The following **Figure 18** shows the parametric derivation of the building dimensions. By adjusting the proportions, the modelled building areas are intended to be closer to the real case buildings and consequently test the level of accuracy of the case studies.

wanted

$$a = \textit{width}$$
$$b = \textit{depth}$$

basic formulars

$$\underset{\substack{\text{above ground}\\ \text{inkl. windows and doors}}}{\textit{external wall area}} = 2 * \textit{height} * (a + b)$$
$$\textit{footprint} = a * b$$

conversion

$$a = \frac{-b * \textit{height} + 0{,}5 * \textit{external wall area}}{\textit{height}}$$
$$a = \frac{\textit{footprint}}{b}$$
$$\frac{\textit{footprint}}{b} = \frac{-b * \textit{height} + 0{,}5 * \textit{external wall area}}{\textit{height}}$$

dimensions

$$b_1 = \frac{0{,}5 * \textit{external wall area}}{2 * \textit{height}} + \sqrt{-\textit{footprint} + \frac{0{,}25 * (\textit{external wall area})^2}{4 * (\textit{height})^2}}$$
$$b_2 = \frac{0{,}5 * \textit{external wall area}}{2 * \textit{height}} - \sqrt{-\textit{footprint} + \frac{0{,}25 * (\textit{external wall area})^2}{4 * (\textit{height})^2}}$$

Source: Own representation

Figure 18 Parametric derivation of the proportions of the early-phase LCA model

(b) Due to different typologies and geometries within a building, it may be important to model different parts of the building as separate volumes with different component templates. This can be tested in Reduzer, where different building parts (e.g., basements or above-ground floors) can be created as separate versions within a project. The results can later be summarized to create a complete building design. In doing so, the touching objects must be considered and manually adjusted if necessary. However, with One Click LCA, it is not possible to create, for example, only a basement without an associated design for the above-ground floors. In Case Study 1, the basement is modelled separately from the above-ground floors, and in Case Study 2, the shed is modelled separately from the main building to better represent the complexity of the building geometry.

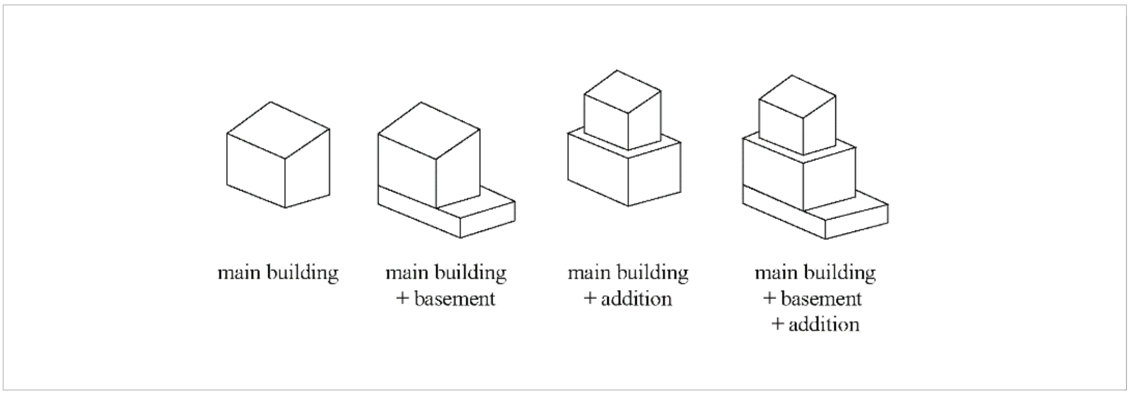


Figure 19 Description of different buildings' complexity

3.2.4 Component Study

The component study provides information about the material templates used. In Reduzer's Automodel, the type of use, as well as the materiality of the construction, is determined by the component template. In OCL's Carbon Designer 3D, on the other hand, the user has a choice of various building component templates, and individual components can be exchanged, regardless of the type of use, to be able to test the influence of different materiality on the design. The study works with the results of the basic early-phase study presented in 0.

Special attention is given to internal walls as they represent an inhomogeneous building element. 'Inhomogeneous building element' in this work means that different construction typologies are used, such as glass partition walls, steel stud walls, or solid walls. The different types of construction can be distributed differently within the grouping of interior walls depending on the project. Considering the **quantity** and **distribution** of the type of internal walls, the influence of the building element specifications and the databases used can be studied.

Accordingly, the number of internal walls was adjusted to the number of internal walls planned in the real case. By eliminating the quantity as uncertainty, the distribution and the allocated emissions can be addressed. Further, the underlying building component structures are investigated with their materials and respective emissions. However, OCL's Carbon Designer 3D has not published the underlying data. The latter point is therefore investigated with Reduzer's Automodel only.

3.2.5 Parametric Study

In the parametric study, the parametric calculation of the number of internal walls by Reduzer's Automodel is investigated. The software queries the average room size as an input parameter. By changing the input parameter from 10 m² to 50 m² in 10 m² steps, it is possible to derive a trend. Due to the complexity of Case Study 1 and the small size of Case Study 2, only Case Study 1 is used for the parametric study.

Subsequently, a separate derivation for the calculation of the number of internal walls has been created by reasoning. This is subsequently tested on Case Study 1 to be able to provide a possible recommended course of action.

$$\text{average room size} = \text{required input parameter}$$

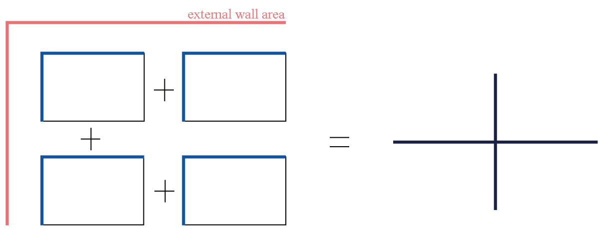
$$\text{no. of rooms} = \frac{\text{GFA}}{\text{average room size}}$$

study of room proportions: a:b (2:1; 3:2; 4:3)

$$\text{length} = \sqrt{\frac{\text{proportion a} * \text{average room size}}{\text{proportion b}}}$$

$$\text{depth} = \frac{\text{average room size}}{\text{length}}$$

$$\text{internal wall area} = \text{no. of rooms} * \text{floor height} * (\text{length} + \text{depth}) - \frac{\text{external wall area}}{2}$$



Source: Own representation

Figure 20 Derivation for the parametric calculation of the number of interior walls

4 Results

The following chapter presents the results of the applied research. The input parameters for the early-phase of the LCA model development are presented in Appendix A and B. In addition, possible model modifications and further investigations are shown.

4.1 Basic Early-Phase LCA

This chapter presents the findings of the basic investigation of Case Studies 1 & 2 focused on the assessment of embodied emission accuracy in the two tools Automodel by Reduzer and Carbon Designer 3D by One Click LCA. The study aims to identify the accuracy and sources of errors leading to guiding and misleading emission prediction. Additionally, discrepancies and equalities in the modelling of various building elements between the tools and the real case were investigated.

Case Study 1 – Vollsveien

Both Reduzer's Automodel and OCL’s Carbon Designer 3D were found to greatly underestimate the embodied emissions of Case Study 1 in their LCA prediction by 38 % and 43 % as can be seen in Figure 21.

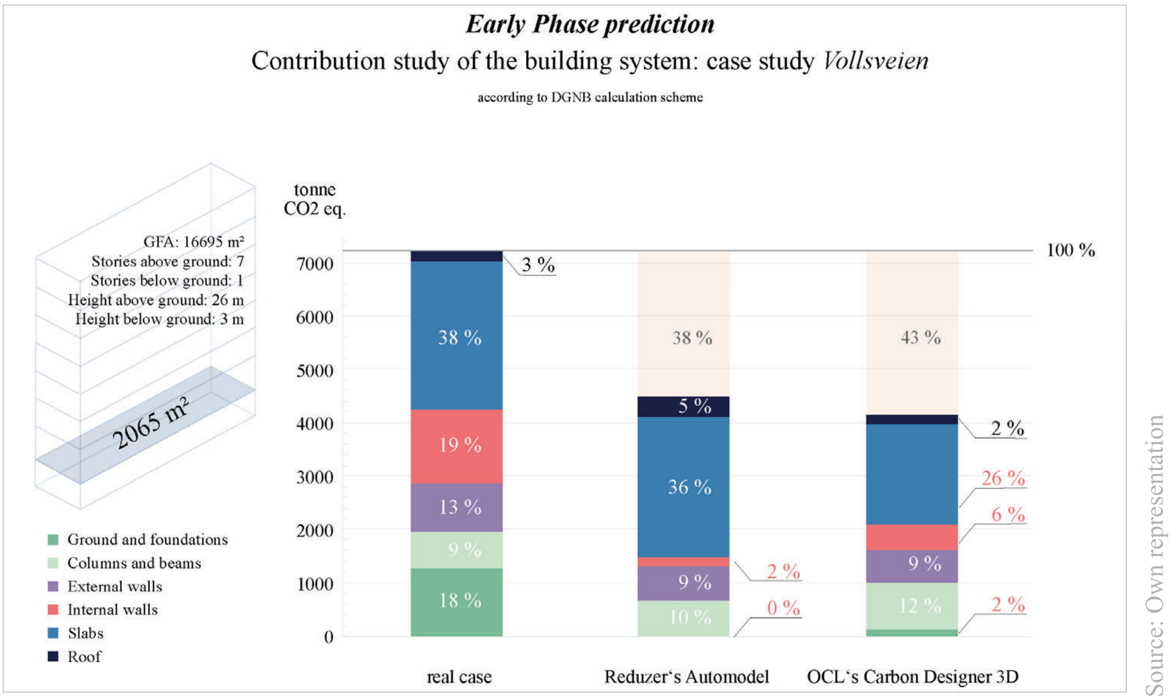


Figure 21 Comparison of early-phase predictions to real case GWP results of Case Study 1

In Reduzer's Automodel, the primary sources of incorrect embodied emission estimation were identified as internal walls, and ground and foundation elements. OCL's Carbon Designer 3D also demonstrates significant underestimation in embodied emissions, with internal walls, ground and foundation, and slabs being the main contributors. These components require further refinement to enhance the accuracy of LCA prediction calculation, others seem to be accurate. An additional notable limitation of Reduzer's Automodel was the undervalue of external wall area, which can significantly impact emission calculation mainly caused by the absence of basement walls. The relatively low emissions per m² of the external wall above ground in the real case may be due to the optimization of the component which has been done during the design process.

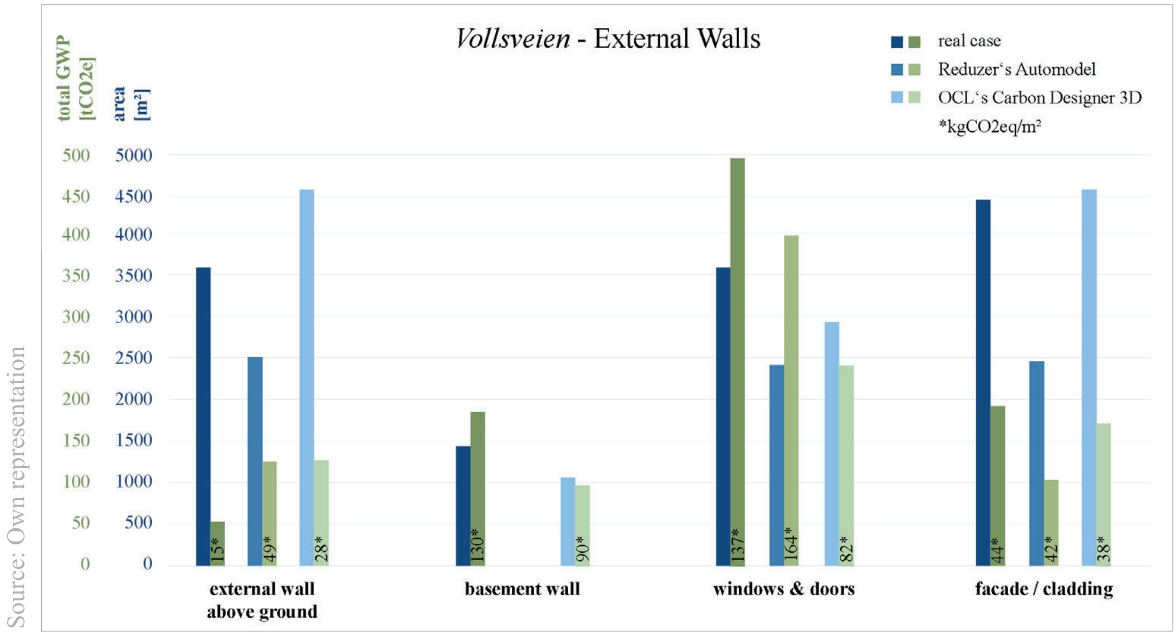
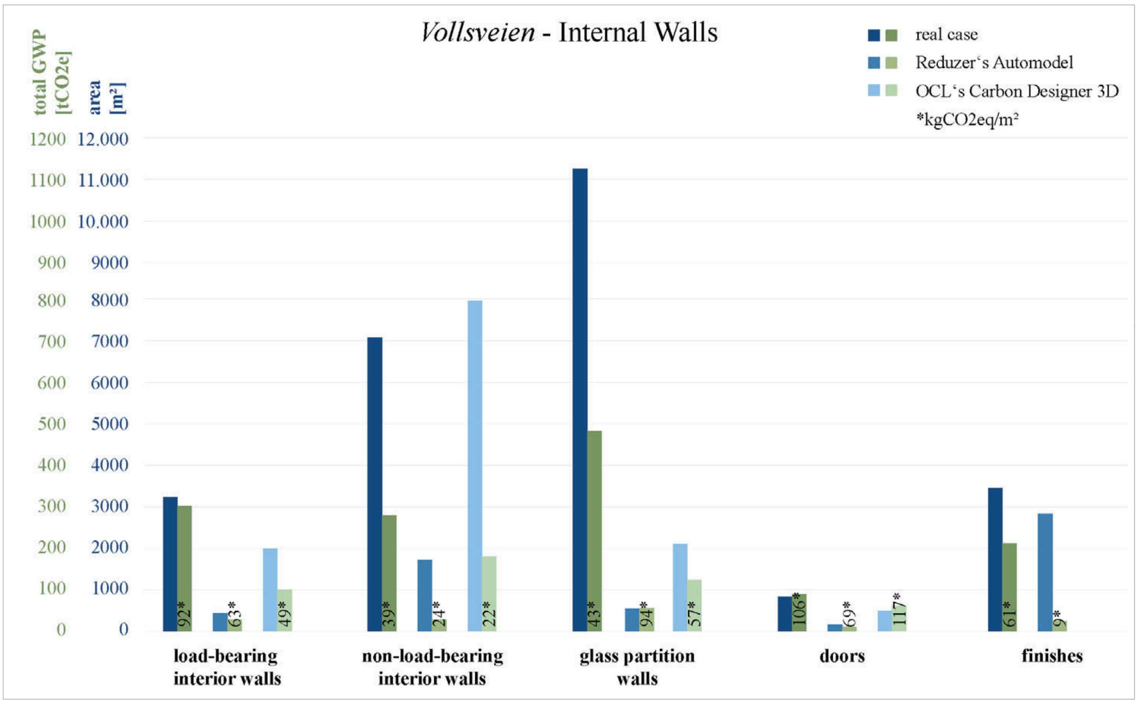


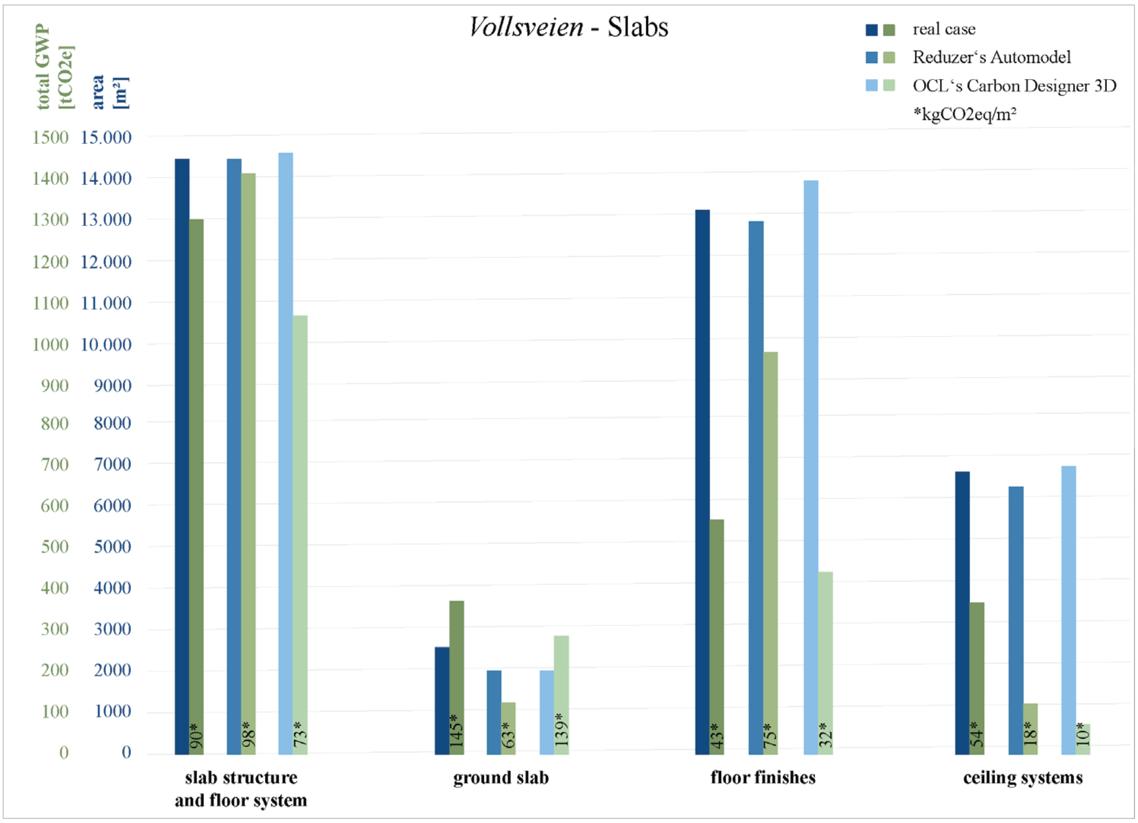
Figure 22 Comparison of the amount and GWP of sub-elements of the *external wall* category between real case and predictions for Case Study 1

Further discrepancies were found in internal wall modelling. Reduzer's Automodel significantly underestimates the number of internal walls in the building design, leading to embodied emission miscalculation. OCL's Carbon Designer 3D on the other hand, overestimates the number of non-load-bearing walls and underestimates the number of other internal walls. Additionally, it links a relatively low GWP/m² to most of the internal walls, contributing to emission undervalue. Both tools also significantly underestimate the number of glass partition walls in the modern office building of Case Study 1. In general, it can be stated that the distribution of construction types of interior wall elements is estimated differently than the reality of Case Study 1. Also, facing shells were either missing or not adequately included in both tools.



Source: Own representation

Figure 23 Comparison of the amount and GWP of sub-elements of the *internal wall* category between real case and predictions for Case Study 1



Source: Own representation

Figure 24 Comparison of the amount and GWP of sub-elements of the *slab* category between real case and predictions for Case Study 1

Reduzer’s Automodel and OCL’s Carbon Designer 3D demonstrated relatively precise estimation of slab areas, indicating that their calculations for this element are reliable. Though, system ceilings were found to be missing or inadequately included in the LCA in both tools.

OCL’s Carbon Designer 3D exhibited a significant difference in GWP per unit in most cases, compared to the real case and, in the case of Reduzer’s Automodel often due to the use of overly well-performing component templates. Balancing the component templates is essential for consistent GWP calculations and should be further studied and discussed.

Case Study 2 – Norwegian Single-Dwelling

In the evaluations for the LCA of Case Study 2, it was observed that both software tools tend to overestimate the GWP for the single-dwelling house. Reduzer’s Automodel exaggerated the embodied emissions for the building elements of slabs and exterior walls. However, it was observed that the number of internal walls continues to be greatly underestimated, which may indicate a limitation in Reduzer’s Automodel software in accurately accounting for this element. OCL’s Carbon Designer 3D also displays an overestimation of the emissions impact of the slab elements, while additionally accounting for too many internal walls.

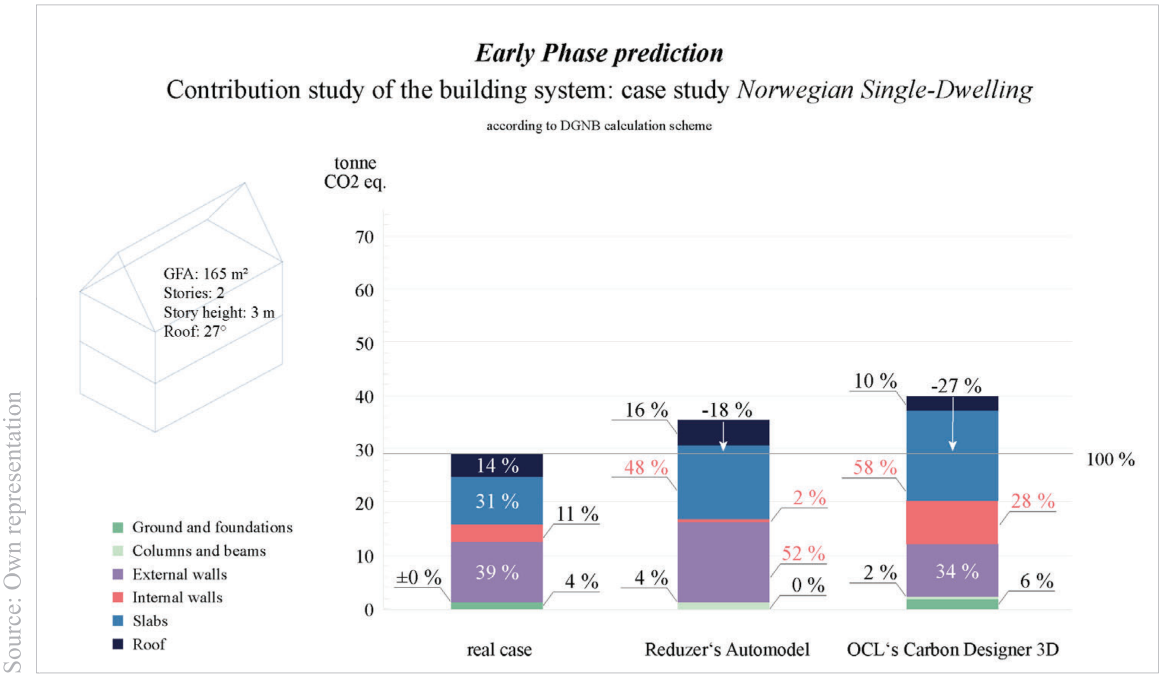
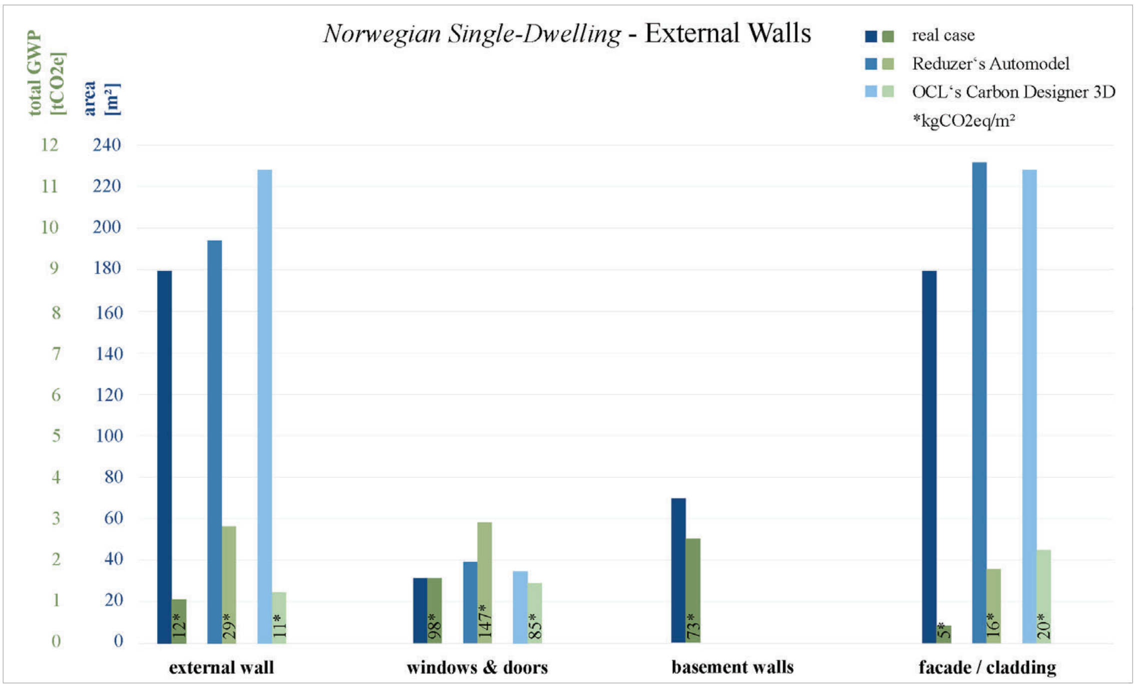


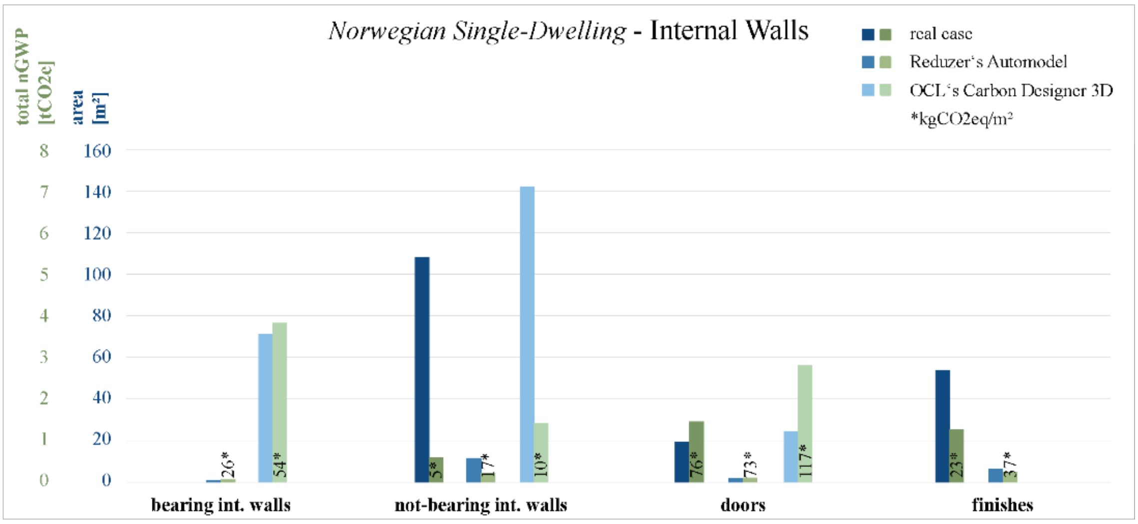
Figure 25 Comparison of early-phase predictions to real case GWP results of Case Study 2

The study revealed that the exterior walls are already optimized in the real scenario, resulting in a relatively high GWP/m² of exterior wall in the predictions. Moreover, the real building design includes basement walls, which is due to the hillside location of the building. In the model's simplifications, this has been particularly neglected, so that no basement walls are included in the LCA of both prediction tools.



Source: Own representation

Figure 26 Comparison of the amount and GWP of sub-elements of the *external wall* category between real case and prediction for Case Study 2



Source: Own representation

Figure 27 Comparison of the amount and GWP of sub-elements of the *internal wall* category between real case and prediction for Case Study 2

Regarding internal walls, Reduzer's Automodel estimates too few internal walls in the simplified model, compared to the real case design, leading to a miscalculation of embodied emissions. OCL's Carbon Designer 3D on the other hand, estimates too many internal walls and doors, contributing to GWP overstatement.

The GWP/m² of ground slabs shows significant differences across the various LCA results. Understanding the reasons for GWP/unit variations is essential for selecting the most appropriate component template for an early-phase LCA and will be further studied in Chapter 4.3. In addition, ceilings were found to be greatly overestimated in the single-dwelling house of Case Study 2 by both prediction tools.

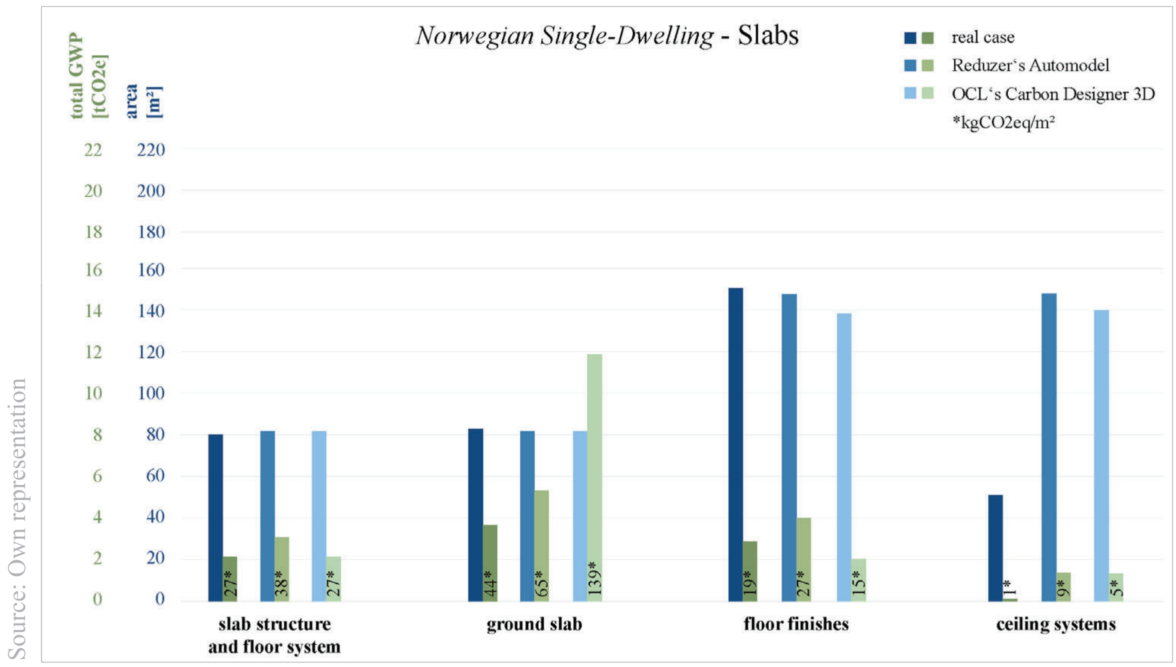
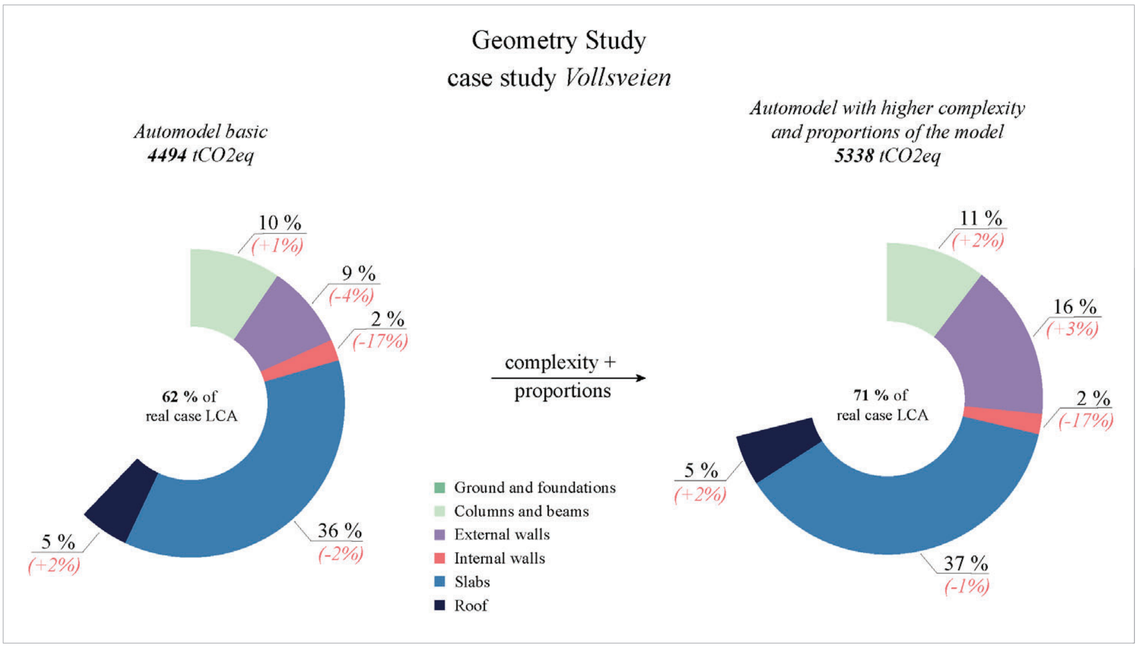


Figure 28 Comparison of the amount and GWP of sub-elements of the *slabs* category between real case and prediction for Case Study 2

4.2 Geometry Study

This chapter presents the results of the investigation with the effects of adding complexity and adjusting proportions of the simplified model for an early-phase LCA. After incorporating complexity and adjusting proportions in the model, the GWP of the building elements of Case Study 1 was found to be slightly overestimated, although the GWP of internal walls was revealed to stay as low as without geometry adjustments in Reduzer's Automodel calculations.



Source: Own representation

Figure 29 Comparison of the GWP of Reduzer's Automodel early-phase model of Case Study 1 *without* considering the proportions and complexity of the design, to the model *considering* the proportions and complexity of the design.

Source: Own representation

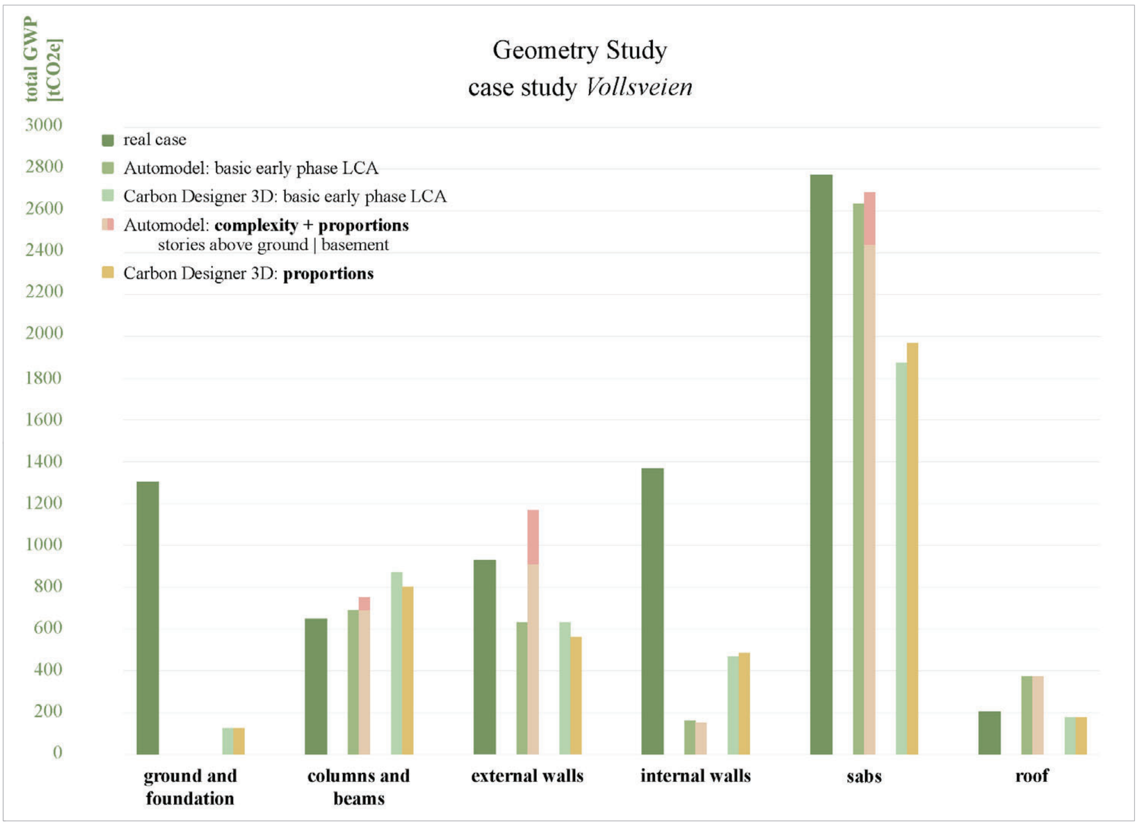


Figure 30 Comparison of GWP per building element of the different modelling approaches of Case Study 1 with Reduzer's Automodel and OCL's Carbon Designer 3D

A significant difference in GWP for Case Study 1 was observed for external walls when complexity was adjusted in the model. Notably, when the inclusion of the basement, which was previously not accounted for in the selected component template, led to an increase in embodied emissions by linking a suitable template to the separate basement volume. This highlights that the absence of components in the component catalogue template results in an erroneous assessment of environmental impacts. Other building elements were not significantly affected by the more precise specification of complexity and proportions (see **Figure 30**).

As shown in **Figure 31**, a more accurate estimation of the outer wall areas could be estimated by defining the complexity (dark gray bars in comparison to the middle blue bars). The results indicate that adjusting the proportions only of the building did not have a substantial impact (light gray bars in comparison to light blue bars).

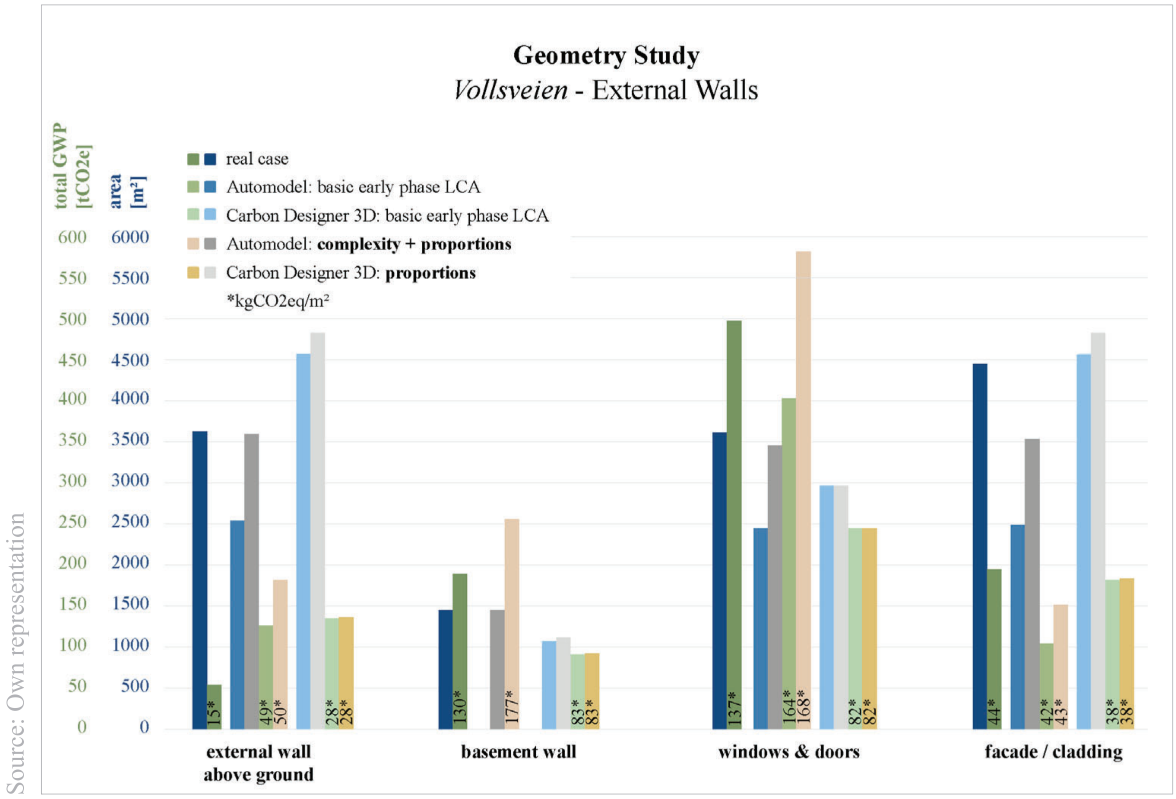


Figure 31 Comparison of GWP and area for external walls of Case Study 1 of the different modelling approaches with Reduzer's Automodel and OCL's Carbon Designer 3D

In contrast to Case Study 1, neither the complexity adjustment nor the proportion adjustment showed a significant difference in GWP. This could imply that the model parameters used for Case Study 2 already adequately captured the real case design, making further adjustments less influential.

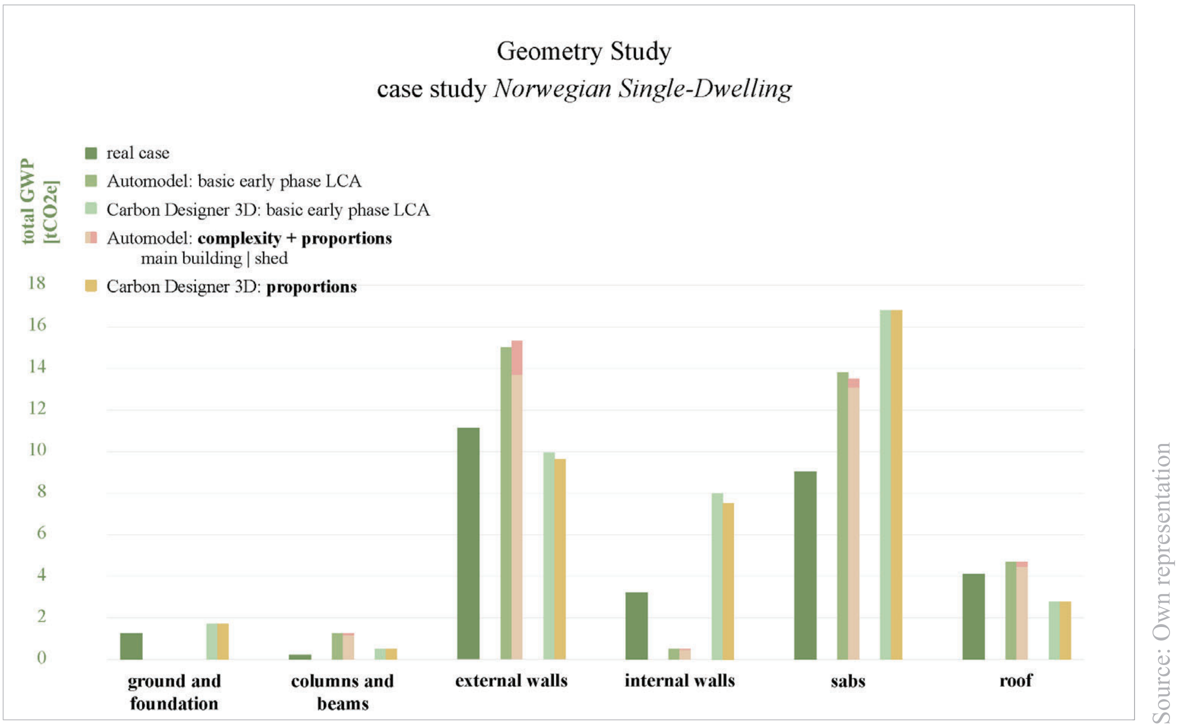


Figure 32 Comparison of GWP per building element of the different modelling approaches of case study 2 with Automodel and Carbon Designer 3D to the real case model

4.3 Component Study

This chapter presents the results of the comparative analysis of GWP estimations of the conducted component study, aiming to understand the variations in GWP/m² value and the impact of the linked component template on the model in each tool. Furthermore, the distribution of construction types of inhomogeneous building elements, like internal walls, and the influence of databases used were investigated. The analysis revealed significant differences in the selection of sample components and their related GWP/m² values when comparing the results from Reduzer's Automodel and OCL's Carbon Designer 3D to the real case LCA calculations. Carbon Designer 3D utilized unique component assemblies, such as hollow-core concrete slabs and sandwich basement walls, deviating from standard reinforced in-cast concrete assemblies used in the real case or Automodel. Their differences in component assemblies contribute primarily to the variations in GWP/m² values of the components between OCL's Carbon Designer 3D and other prediction tools like Reduzer's Automodel. In the Automodel calculation, the bituminous sheet appears to contain an error in the GWP dataset. 75 $kgCO_2eq/m^2$ is very high, instead, according to different EPDs, the value is around 5 – 10 % of the stated GWP value [74, 75].

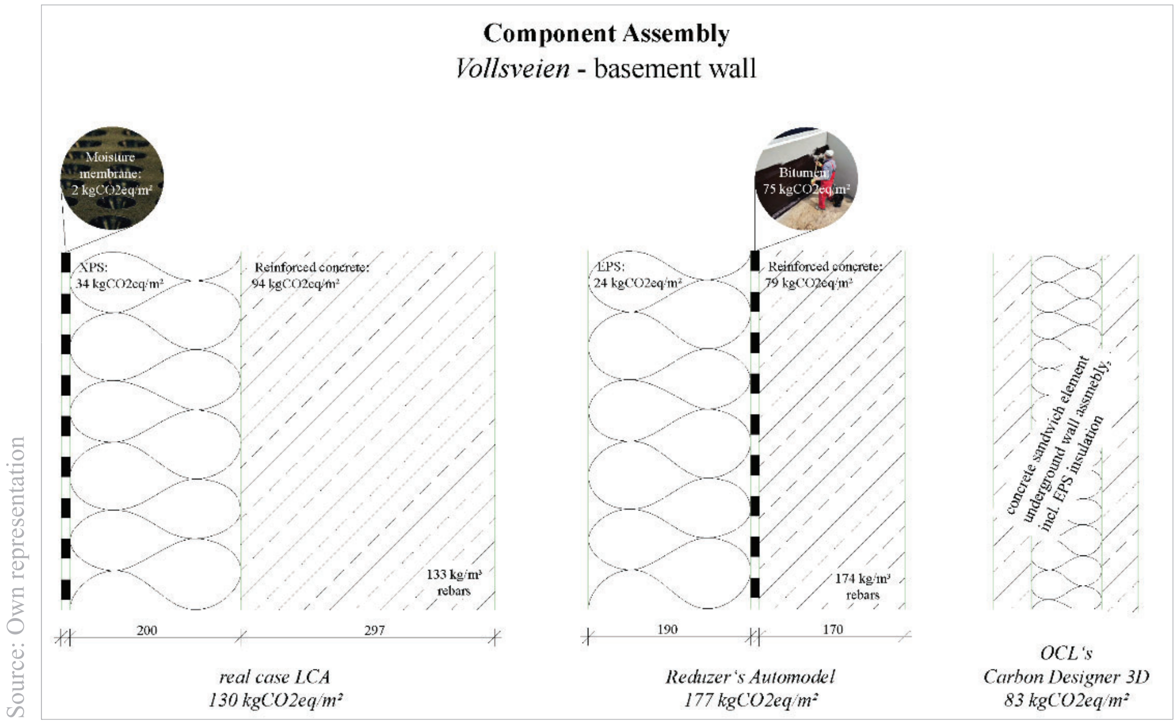


Figure 33 Comparison of the different component assemblies of basement walls of Case Study 1 in the real case to predictions

Adjusting the number of internal walls to the real scenario required 7.65 times more internal walls in the simplified model created by Automodel and 1.76 times more internal walls in the simplified model created by Carbon Designer 3D. This result highlights the flawed estimation of LCA tools of the number of interior walls for an accurate representation of the real case design. After the number of internal walls has been adjusted to the common number of the real case, Reduzer's Automodel GWP estimations were found to be comparable in the total amount of GWP for internal walls and in the distribution of GWP of different construction types of internal walls to the real case scenario, indicating its relative accuracy. However, the distribution of the areas of construction types in Automodel differed significantly from the real case. Carbon Designer 3D exhibited a similar contribution of areas of different construction types to Reduzer's Automodel although also deviating from the actual distribution of the real case. It is striking, though, that both the total emissions are much lower in Carbon Designer 3D's prediction and the distribution of the emissions among the types of construction deviates from the real case and Automodel. This large deviation can be explained by different underlying component assemblies and datasets.

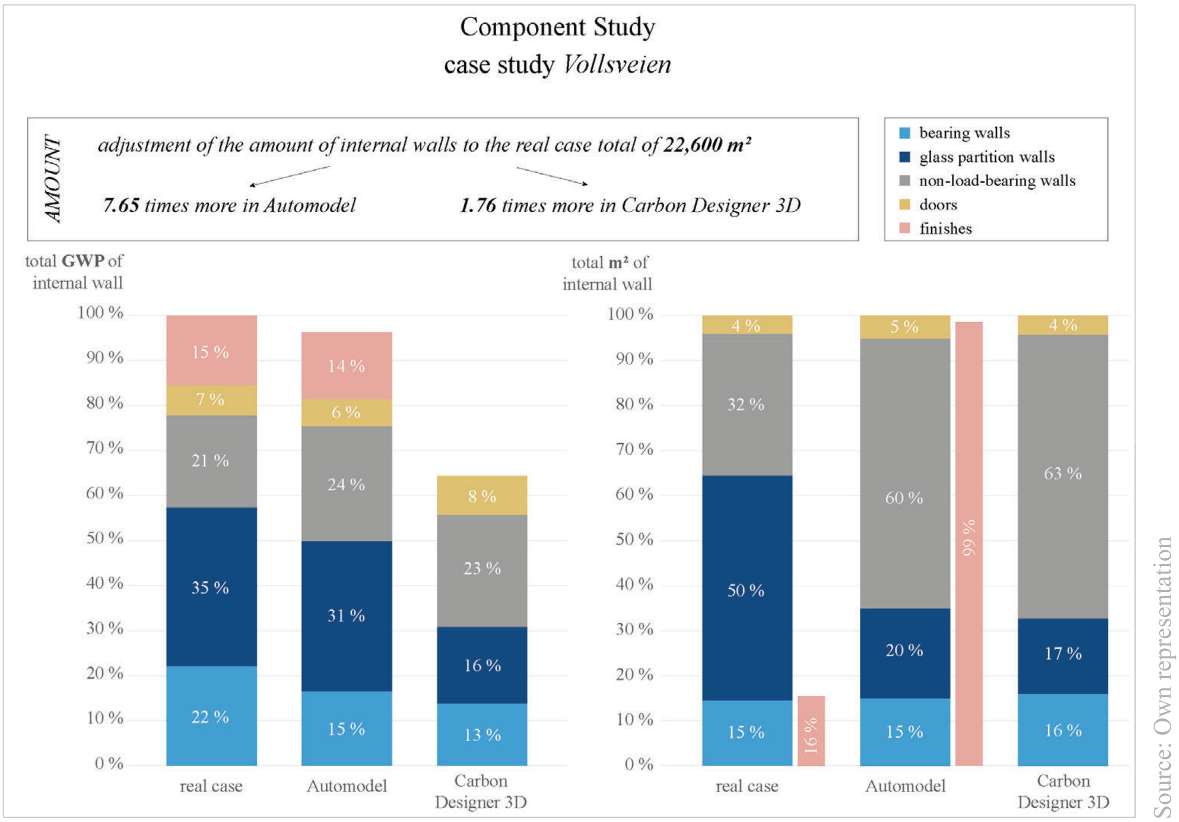


Figure 34 Study of the amount [m²], distribution [%] and GWP impact of internal walls in Case Study 1

Examining the components used for internal walls in the different LCA calculations of the real case, Reduzer's Automodel and OCL's Carbon Designer 3D revealed significant variations in GWP/m², even for seemingly standardized components like drywall (steel stud walls). Here, the real case accounts for 39 kgCO_2eq/m² for steel stud walls, Reduzer's Automodel only 24 kgCO_2eq/m² and OCL's Carbon Designer 3D 15 kgCO_2eq/m². As can be seen from **Figure 35**, the different calculations not only use different component structures with different GWP values but also use different construction types within a grouping. Even if a 100 mm thick steel stud wall appears standardized at first glance, it is noticeable that the component structure is calculated differently in the separate LCA calculations and various databases or EPDs were used for comparable products in each assessment. For example, the 100 mm steel stud wall in Automodel has a 100 mm thick mineral wool layer between the gypsum boards. In the real case, the mineral wool layer is only 50 mm thick, with the remaining 50 mm being an air layer. The steel stud spacing also differs, which can be seen in the kg/m² steel value in **Table 10**. Particularly noticeable are the high emissions from paint in the real case. Automodel does not list paint in the component structure of the steel stud wall but declares it separately as a surface treatment. Generally, the relatively long service life of 60 years of the non-load-bearing interior walls in an office building should also be questioned, as renovations take place more regularly.

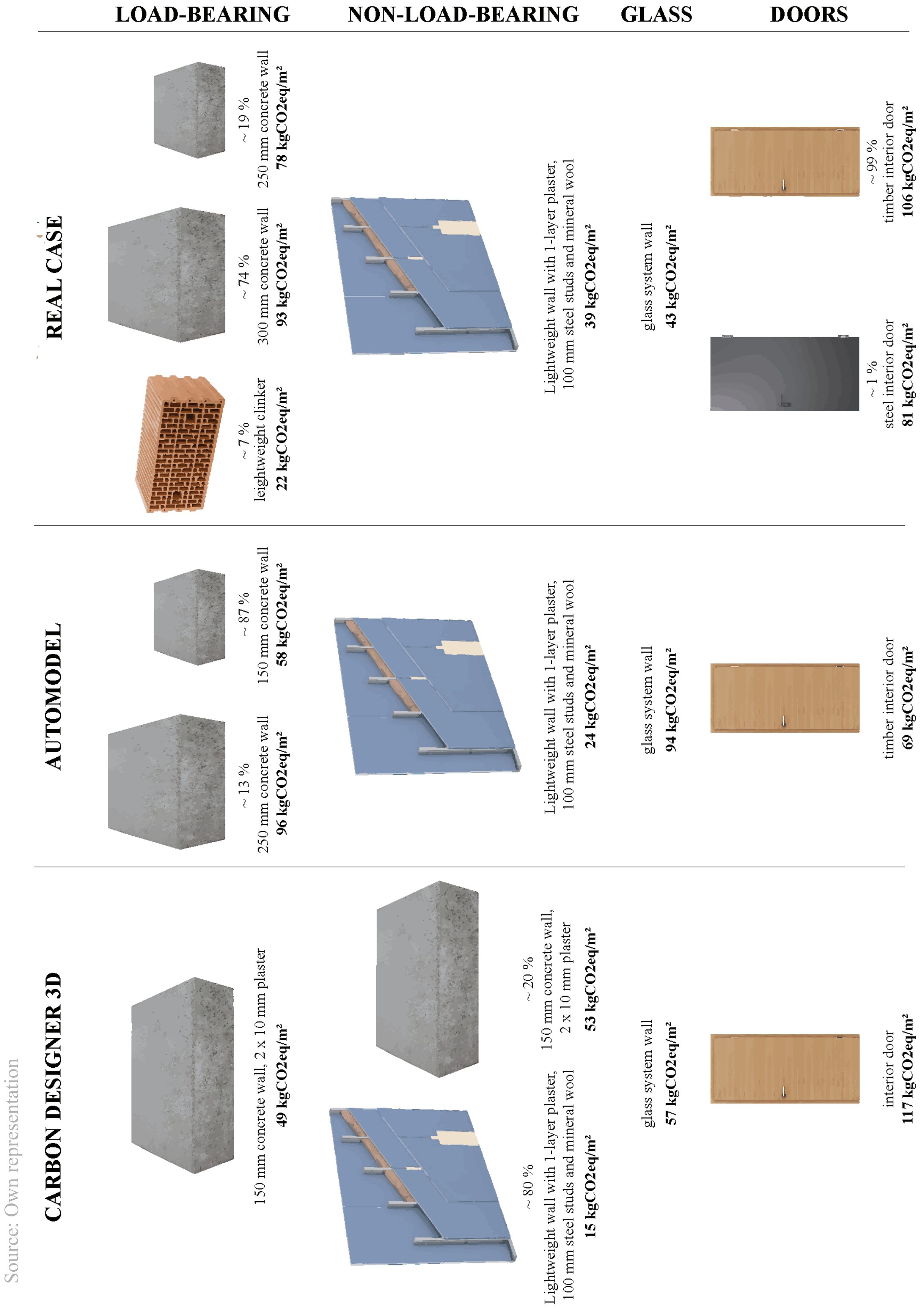


Figure 35 Illustration and comparison of the components used for internal walls in Case Study 1

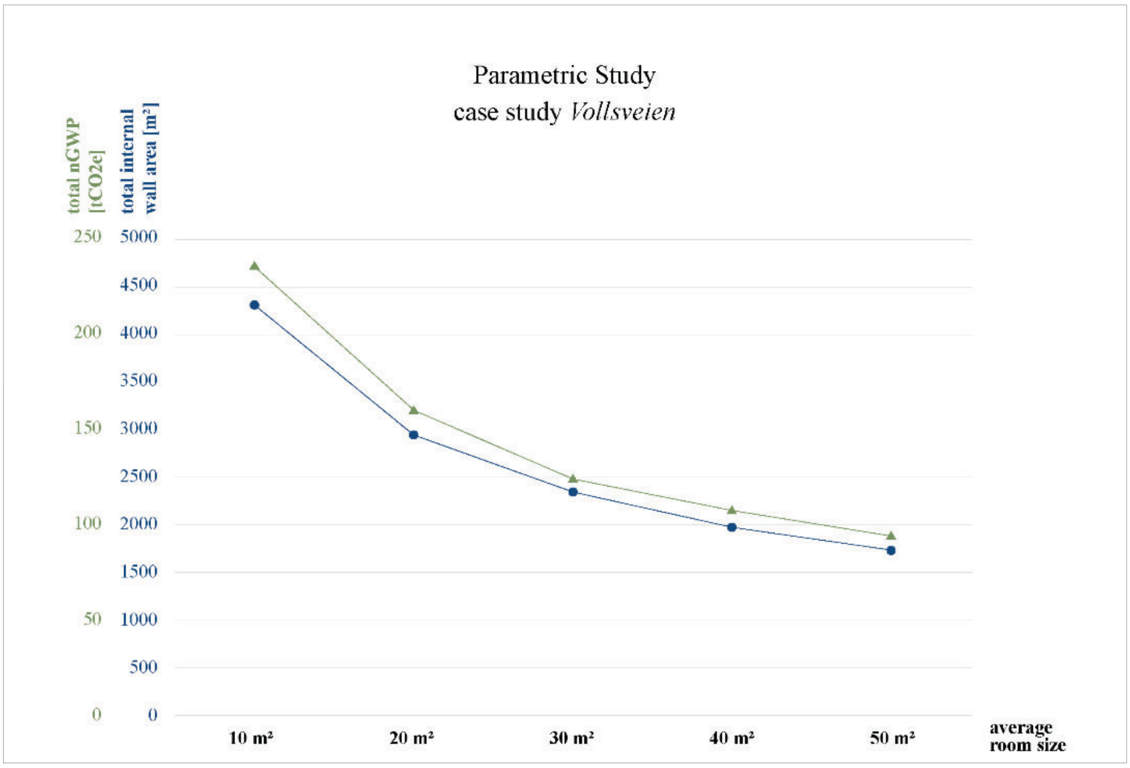
Table 10 Component assembly of steel stud walls in Reduzer's Automodel LCA compared to the real case LCA in Case Study 1 (the grey line is not included in the component but listed separately as surface treatment) (own representation)

	Material	Amount	Transport distance [km]	Estimated service life [y]	Wastage [%]	GWP/m² internal wall [$kgCO_2eq/m^2$]	GWP [$kgCO_2eq/m^2$]
Automodel	Gypsum board	2 x 12,5 mm	500	40	15	**11,5**	**23,9**
	Mineral wool	**100 mm**	**500**	60	10	**4,1**	
	Steel stud	**2,8 kg/m²**	2000	60	**10**	**8,0**	
	Thin steel profile	**0,1 kg/m²**	**2000**	**60**	**10**	**0,3**	
	(Paint	0,27 kg/m²	500	10	10	3,0)	(26,9)
Real Case	Gypsum board	2 x 12,5 mm	500	40	15	4,1	39,2
	Mineral wool	50 mm	65,5	60	10	0,6	
	Steel stud (reusable)	1,4 kg/m²	2000	60	3	1,9	
	Paint	**0,13 kg/m²**	**500**	**15**	**10**	**32,6**	

4.4 Parametric Study

This chapter presents the results of the investigation into the relationship between average room size, room proportions, and the number of internal walls in Reduzer's Automodel. The study aimed to understand how changes in the parameter 'average room size' influence the estimation of internal walls in the early-phase model generated by Automodel. However, it is unclear how such large discrepancies between the modelled number of internal walls and the real case could occur. The parametric conclusions by Reduzer's Automodel are not transparent to the author. An own derivation has been introduced in chapter 3.2.5, which has been subsequently compared to Reduzer's Automodel parametric calculation results to investigate the predicted trend.

The analysis revealed a notable relationship between average room size and the number of internal walls in Automodel. As the average room size increased, the number of internal walls decrease exponentially. The internal wall area is also directly related to the total GWP of the internal walls.



Source: Own representation

Figure 36 Area and GWP trend of the interior walls of case study 1 when changing the parameter 'average room size' in Reduzer's Automodel

To confirm the observed exponential decline, an own derivation was performed using the data from Case Study 1. The derivation corroborated the findings, providing evidence for the exponentially declining relationship between room size and the number of internal walls in Reduzer's Automodel. The study proved that Automodel significantly underestimates the number of internal walls. This underestimation is likely due to a wrong parametric derivation by the software. As a result, the estimated internal wall area in the early-phase building model may not accurately reflect the actual internal wall requirements in a real case scenario.

Interestingly, the study found that room proportions did not have a significant influence on internal wall area when the general building has been modelled within the proportions of 3:2, which is a default value (editable) in Automodel. Despite variations in room proportions, the software consistently exhibited an exponential decline in a comparable range. Based on the derived relationship between average room size and the number of internal walls, the study estimated the average room size in Case Study 1 to be approximately 23 m², which is close to the default suggestion of Reduzer's Automodel of an average room size of 20 m² and appears creditable according to the IFC model of Case Study 1.

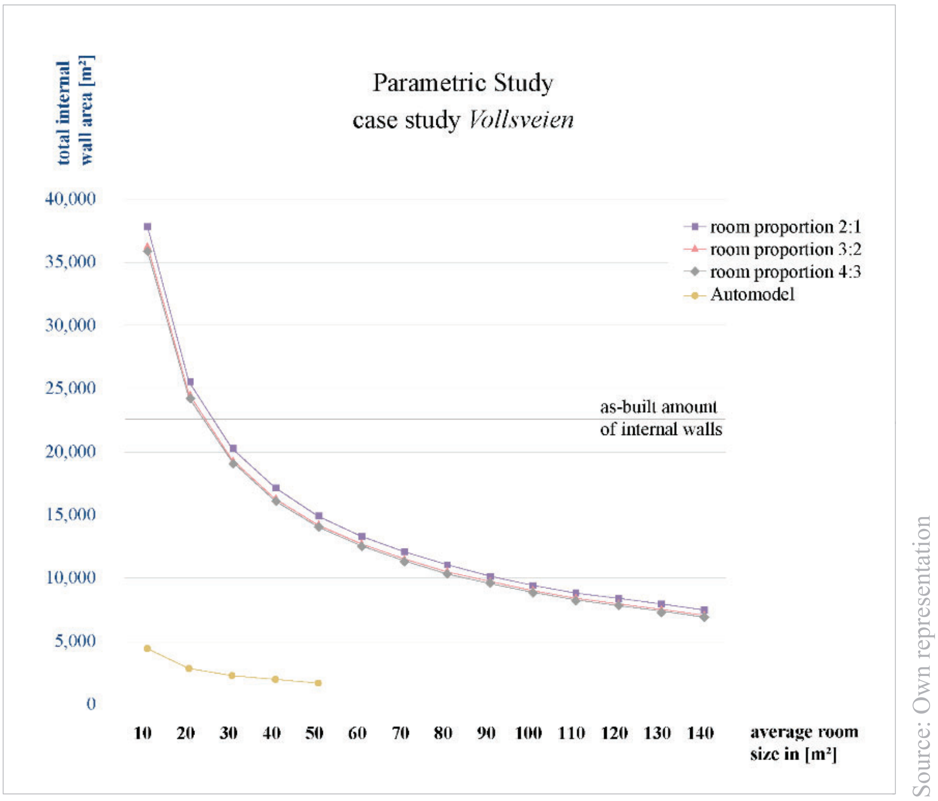


Figure 37 Illustration of the derived calculation of interior wall areas with room proportions 2:1 (purple), 3:2 (pink), and 4:3 (grey) in comparison to Reduzer's Automodel parametric derivation of interior wall areas (yellow)

5 Discussion

The accurate prediction of GHG emissions in building design is pivotal for informed sustainable decision-making during the design process, facilitating the achievement of overarching sustainability objectives. A multitude of prediction tools have been devised to estimate embodied GHG emissions during the initial phases, employing diverse methodologies. However, the veracity of these predictions in real-world scenarios and their capability to guide precise design choices warrant further investigation. Two exemplary early-phase LCA prediction tools, namely Automodel by Reduzer and Carbon Designer 3D by One Click LCA, have embarked on the mission of creating parametrically driven simplified models. These models serve as the foundation for their early-phase LCA calculation, effectively addressing the existing knowledge gaps surrounding design decisions that remain unexplored at the conceptual stage. This scientific discourse seeks to scrutinize the alignment between parametric predictions and real-case GHG emission outcomes, substantiated by case studies involving the aforementioned tools. The ultimate objective is to ascertain the feasibility of deriving consequential design determinations from these predictions. It is important to note, however, that for a comprehensive evaluation of the project's environmental impact, it is imperative to delve beyond the GWP indicator. Supplementary indicators such as the PENRT should also be considered in the projections. Thus, this endeavor represents only a fraction of the broader spectrum of activities necessary for an all-encompassing early-phase LCA. Moreover, it should be acknowledged that drawing universal conclusions based solely on the investigation of two disparate case studies is premature. To establish empirically substantiated inferences, it becomes essential to broaden the horizon by incorporating additional case studies and potentially engaging in comparative analysis of findings of other studies listed in the existing literature.

Despite these limitations, the exploration of diverse early-phase LCA tools, coupled with the case study utilization of the two parametric LCA tools Automodel by Reduzer and Carbon Designer 3D by One Click LCA via case study analysis, reaffirms the criticality of inclusivity across all parts of a building design. The inclusive approach of parametric modelling is pivotal for accurately approximating the cumulative impacts of the entire building already at an early design stage. Only through a comprehensive representation of the entire building system within the LCA framework can the key sources of GHG emissions be elucidated, thus enabling well-informed design decisions.

The conducted applied research showed, that the GWP results from the prediction tools are within a comparable range but deviate significantly from the real case LCA results. It can be questioned whether absolute numbers as GWP results at an early-phase make sense as high uncertainty at the beginning of a design process surely change the value to a great degree, or if a different rating system, like a color scheme or group classification of e.g., 'excellent', 'good', 'average', 'bad' indicating the environmental performance of the used materials would be more appropriate. However, some countries have introduced mandatory LCAs for buildings in the meantime. Only some of them require compliance with a benchmark. Therefore, during the design process, planners and builders must obtain an as accurate forecast as possible of the GWP of the embodied emissions to be able to achieve the targets. To avoid misleading stakeholders with absolute values by implying that the calculated predicted value is equal to the final calculated emissions, it should be considered to include early-phase uncertainties in the result by giving a range of possible GWP results through prediction tools. For example, one can include GSA as Resch et al. suggest in the publication "Estimating dynamic climate change effects of material use in buildings – timing, uncertainty, and emission sources" [38].

A major problem with the inaccurate total GWP prediction of a project is the erroneous inclusion of emissions for the building element 'ground and foundation'. As the case studies have shown, the estimation of embodied GHG emissions varies enormously for this building element and is quite random. On the one hand, it is important to conduct further research on the dependence of the GWP of the 'ground and foundation' of the project on other parameters, such as the number of stories, structural material, ground conditions, etc., to be able to parametrically infer the emissions already in the early-phase. However, it must be questioned whether architects have a major influence on the emissions of the building element 'ground and foundation' during the design phase, or whether these cannot be optimized anyway as the location, and user requirements are set and therefore might be neglectable in early-phase LCA calculations. Nevertheless, the possible influence of architects on emissions from 'ground and foundation' should be further investigated.

The study also revealed that complex building geometries and particularities like the hillside location of the project, such as in Case Study 2, are not well represented by simplified building cubes. Adjusting the building model's complexity to reflect the actual building design to a higher degree results in more accurate GHG emission prediction. For example, to consider the hillside location of the project, a checkbox could be used to query which exterior walls of the respective stories are in contact with the ground, to be able to select a suitable component template for these elements and to adjust the WWR. Different building parts can be modelled as separate volumes, whereby non-adiabatic (non-envelope) elements should be marked to avoid double counting. The adjustment is important when the structural material or construction typology of certain building parts differs from other building parts significantly, like basements in comparison to the above-ground building. Looking at the results of Case Study 2 shows that a simple design like the single-dwelling house, may not require higher complexity, as the prediction tools already include the complexity of the building to a sufficient degree; whereas a complex design like Case Study 1 benefits from accounting for the intricacies of different building parts. However, it is questionable whether the information about the planned complexity is already available at the beginning of a design process. Therefore, it might be enough for smaller building projects to include component catalogue templates, which account for all different building parts. If templates offer all the necessary components of the building, additional complexity in the model might therefore not be required. However, allowing users to map and control the used component catalogue templates to the different building parts, which have been defined through the complexity of the model, could offer more accurate, comprehensible, and flexible customization.

Looking at the LCA results of the real cases showed that some components involve incorrect allocations of materials. For instance, in Case Study 1, about 4700 m² of internal walls, named ‘Uni Wall systemvegg, 98 mm, 3600x2700 mm, 9.72 m², 3343 kg, UniWall 98 mm (Moelven Modus)’, were indicated to be a glass partition wall but were linked to generic data of normal plaster in the category of building boards, resulting in an incorrect GWP value. In addition, the materials of non-load-bearing internal walls were assigned a service life of 60 years. The long service life of non-load-bearing internal walls in an office building is to be questioned as renovations and user change appear to happen every 10 to 15 years and the materials are then often disposed of sooner [76]. However, errors like these are also still active in prediction tools such as Reduzer’s Automodel. For example, a far too high GWP was assumed for the bitumen layer on basement walls in the office building template (see Chapter 4.3). The compilation of LCAs therefore still requires a high level of expertise from the user to avoid errors of this type. However, it is essential to ensure that such sources of uncertainty are nearly eliminated in the development of component catalogue templates to be able to avoid linking up errors in the design process.

Moreover, optimized components in component templates in terms of GHG emissions of prediction tools may lead to underestimating GWP and overshadow the importance of specific components' contribution to the total amount of embodied emissions of the project. This was demonstrated by the OCL's Carbon Designer 3D prediction tool, where, for example, sandwich elements were used as basement walls or hollow-core concrete slabs were used in the template for standard concrete buildings in Norway. This emphasizes the need for considering multiple component assemblies and discussing whether to use standard, overestimated or underestimated templates. Whereas an overestimation of some components' GWP has the potential to highlight the importance to make optimization decisions during the design process, the predicted GWP may be too high compared to the final LCA of the project. Using underestimated components instead may result in a comparable GWP value of the prediction to the final LCA where optimization has already taken place. The most reasonable solution could therefore be to use standardized assemblies for the early-phase LCA calculation as a reference. As in different national contexts, different building materials are typically used, the question arises of which component assembly can be considered as a standard component in the context. The development of empirical national standard component catalogues could solve this dilemma. Those standard building lists could then be the basis for an early-phase LCA prediction. Considering the underlying material information, a general data set would be useful in order not to include specifications of individual products. Giving a range of possible GWP values for a particular material or product could show the potential for optimization in the component and help architects make decisions.

To be able to make material decisions for the project, it has proven to be highly beneficial to use a drop-down menu to select from different types of construction for the respective components to make their influence on the project visible. It would be beneficial to create dependencies of construction setups that are compatible with each other and to exclude combinations that would not be feasible in reality. OCL's Carbon Designer 3D offers this simple form of investigation. In Reduzer's Automodel it is more complicated to exchange assigned products and materials to a component. However, in different versions of a project, different building templates with respective component structures can be selected. The selection of different templates is limited though. For office buildings e.g., only one selection option, concrete construction, is available in Automodel. Reduzer's approach would function well, provided that a larger selection of component catalogue templates for building constructions is available. However, modification of individual components is not possible through the general replacement of an entire building template.

Nevertheless, the construction-related dependencies of component structures could be considered in this manner without difficulty.

Both early-phase LCA tools investigated showed large discrepancies in modelling the correct number of interior walls. However, the own derivation confirms that the parametric derivation of interior walls is manageable. In addition to the correct prediction of the number of interior walls, the distribution of construction types within the inhomogeneous building element with their assigned GWP is of enormous importance for an overall accurate GWP prediction, which could be investigated through empirical data. **GWP/unit**, **quantity**, and **distribution of different construction types within a building component**, therefore, influence the total emissions of the building element. The assumptions of the three parameters should be as accurate as possible to obtain matching results. By adjusting the number of interior walls to the true planned amount, however, it can be demonstrated that the influence on the total emissions can already be better estimated, and design decisions can be taken more effectively. Thus, it can be stated that it is of high relevance to estimate the component quantities in the simplified model of the early design phase with maximum detail and to parametrically model a complete building design with appropriate component dimensions. Only if the model is as accurate as possible, there is a chance to estimate the GWP of the building project in the early-phase and to highlight decisive building elements appropriately for further investigation.

Based on the outcomes of the conducted research, it has been observed that certain additional measures, such as suspended ceilings or facing shells, have not been adequately accounted for in the tested parametric prediction models. The incorporation of these measures is essential not only from a design perspective but also to address concerns related to e.g., the building's acoustic performance or the necessity for installation levels. To achieve a complete early-phase LCA calculation, it is imperative to include such measures in the assessment. However, the implementation of these measures often relies on factors like the typology, size, or regulatory guidelines governing e.g., building acoustic requirements. Therefore, estimating the proportion of facing shells and suspended ceilings necessitates the use of inquiries. For instance, the aimed building's acoustic quality could be roughly indicated using checkboxes denoting high, moderate, or low-performance levels according to the national requirements, which subsequently influences the percentage of measures in relation to the surface area of slabs and walls. Similarly, in the context of office buildings or multifamily homes, installation levels could be assumed and expressed as a percentage based on standardized assumptions or empirical available data.

The proposed method can also be applied to the building envelope. By utilizing check-boxes, architects could specify the desired insulation level, enabling parametric determination of insulation thickness and component structure. This straightforward querying process empowers architects, and other project stakeholders, to explore the designs more efficiently and make informed decisions about the measures they wish to incorporate, even if it results in higher embodied emissions and those that may be omitted. Additionally, this approach fosters a more comprehensive evaluation of various design options, allowing architects to strike a balance between environmental considerations, technical requirements, and design decisions. By making use of the simple query system through check-boxes, architects can optimize their designs for sustainability while ensuring the practicality and performance of the building. This ultimately facilitates the creation of energy-efficient, technically functional, and environmentally responsible buildings, aligning with modern-day sustainable building practices.

6 Conclusion

The research questions posed at the outset are answered in the following chapter. Besides the presentation of the decisive parameters for an early-phase LCA according to the findings of the present work, the tools Automodel by Reduzer and Carbon Designer 3D by OCL are evaluated in terms of prediction accuracy, usability, and scope. To conclude, a recommendation for improvement of the Automodel tool is given to better estimate future projects in terms of embodied GHG emissions already in the early design phase.

Decisive Parameters of Early-Phase LCA

In the literature review and the case study investigations of this thesis, the identification and understanding of decisive parameters prove pivotal in ensuring the accuracy of embodied GHG emission assessments at an early stage. The following bullet points encapsulate these critical parameters and their significance within the context of early-phase LCA.

General Building Information:

- The accurate modelling of the *general geometry*, encompassing width, depth, height, and the number of stories, plays a vital role. While proportions are not as significant as modelling the complexity of the design; capturing different typologies; it is crucial to represent all the various building elements in the early-phase building model through the help of parametric modelling. Parameters such as *window-to-wall ratio (WWR)*, *average room size*, *roof type*, *assembly thickness*, and *percentage of load-bearing internal walls* contribute to the overall environmental impact and should be considered already at an early-phase.
- The selected *LCA approach* or calculation scheme sets the foundation for the analysis, determining how impacts are assessed and compared.
- Establishing a *functional equivalent* ensures that different design options serve the same purpose and are evaluated based on equivalent functionalities.

Building Structure

- Adapting the hierarchical building structure according to the *national context* is essential to reflect local construction practices and regulations. In addition, LCA calculation results may differ due to a change in how the building is hierarchically structured. Accordingly, a continuous hierarchical building structure should be maintained from the screening LCA calculation throughout the project process to the complete LCA calculation.

- Utilizing the *same components as in the as-built LCA* by compensating for missing information at an early-phase through parametric assumptions allows the whole building design to be calculated. This enables a more accurate GWP value to be predicted for the real case, highlighting the important parameters where design decisions need to be made.

Material and Product Information

- Employing *standard component assemblies* relevant to the national context is crucial, avoiding miscalculation of the GWP/unit of building components. These can be provided in predefined component lists, at an early-phase.
- The use of *general data* instead of product-specific EPDs helps to represent the average environmental performance of a material to exclude particularities of individual products in the estimation. It also illustrates that material-related design decisions have not yet been made at the early stage.
- Introducing a potential *range of GWP per material/product* aids in highlighting improvement opportunities within material and product choices.

Parametric modelling

- Carefully crafted *assumptions* of building element quantities ensure a holistic representation of the building. The consideration of these assumptions affects the reliability and accuracy of the early-phase LCA. Ensuring an *accurate quantity estimation of building components* is crucial for a precise total GWP estimation. The distribution of different construction types within a building component and the selection of materials and products further refine the building modelling as secondary parameters.
- Employing a method of *reasoning and testing* allows for a robust exploration of various design scenarios and their environmental implications.

Accuracy of Reduzer's Automodel and OCL's Carbon Designer 3D

The examination illuminates that both Reduzer's Automodel and Carbon Designer 3D by OCA offer GWP prognostications. However, their precision falls short of aligning with the GWP outcomes of the case studies. Nonetheless, the allocation of total emissions among various building components are well estimated, with exceptions observed for 'internal walls' and 'ground and foundation' elements. This deficiency can be attributed to inadequate parametric estimation of these elements within the models. Furthermore, discrepancies are noticed in the predictions for 'exterior walls', particularly when different building typologies are employed in a single design, such as comparing basement walls to upper-floor exterior walls. This mismatch arises from incongruences between the assigned component catalogue template and the actual design, signifying a need for synchronization. In general, the inaccuracies in predictions stem from insufficient modelling, as well as discrepancies in component allocation or misjudgments of component assemblies that result in the miscalculation of GWP values. These aspects warrant further exploration. Noteworthy is the finding that simpler building configurations yield predictions of higher accuracy compared to larger and more intricate structures. This divergence in accuracy can be ascribed to the augmented uncertainty inherent in complex geometries and intricate building typologies. Despite this variation, both tools produce GWP approximations falling within a similar range. This outcome underscores their potential as tools for aiding decisions and providing support in assessing environmental impacts during the early-phases of design. However, an accurate estimate of embodied emissions of the building design at an early stage is not yet possible with Automodel, nor with Carbon Designer 3D.

Usability of Reduzer's Automodel and OCL's Carbon Designer 3D

Both tools are found to be user-friendly, providing intuitive interfaces and input parameters that facilitated their utilization. While certain input parameters are left untouched in this evaluation, their potential for adjustment during the design process is recognized. The visualization capabilities of Carbon Designer 3D are praised for enabling users to gain a clear understanding of the generated model, aiding in visualization and comprehension of the design. The capacity to generate complex geometries in Reduzer's Automodel is noted, although the process requires the creation of different versions. Enhancing the tool's ability to generate complex geometry in a single version is proposed, which would simplify the design approach and minimize issues related to double counting of touching components. Both Reduzer's Automodel and OCL's Carbon Designer 3D are identified as effective tools for refining component definitions throughout the design process. This flexibility supports designers in making informed decisions as the design evolves. A notable advantage observed of Carbon Designer 3D is the ability to modify individual components from a selected list without needing to replace the entire component catalogue template.

This feature streamlines the exploration of various design decisions and their corresponding impacts on environmental performance. The separation of the predefined component catalogue and typology parameters within Carbon Designer 3D is commended, as it allows for a more accurate representation of the building's structure and usage type. The ease of changing the calculation scheme in Reduzer was highlighted as a valuable feature, enabling users to adapt their approach as the design progresses. In contrast, OCL’s Carbon Designer 3D requires users to commit to a specific calculation approach at the outset, limiting flexibility in this regard. In conclusion, the usability assessment of Reduzer's Automodel and OCL’s Carbon Designer 3D reveal several positive aspects that enhance their effectiveness as decision-support tools for sustainable building design. While both tools demonstrate strengths, there is potential for further enhancement, particularly in areas related to generating complex geometries, integrating various design considerations, and refining the modelling and parameterization processes.

Scope of Reduzer’s Automodel and OCL’s Carbon Designer 3D

Both early-phase tools focus solely on calculating GWP for the main building and do not include elements such as PV systems, external installations, or technical equipment. However, they possess the capability to integrate additional elements, expanding their scope beyond the main building later in the process.

Improvement suggestions for Reduzer’s Automodel

During this study, the assessment of Reduzer's Automodel has identified areas where potential improvements can enhance its efficacy as a sustainable building design tool. The following improvement suggestions have been identified:

Different Accounting for Internal Walls: To enhance accuracy, refining the accounting methods for internal walls, like the one introduced in this thesis, could lead to more reliable predictions, and mitigate the current underestimation or misallocation of emissions associated with these elements.

Use of Generic Product Data at an Early-Phase: Incorporating generic product data, possibly in the form of a range of GWP values, during the early design phase could enable designers to make informed decisions despite limited information availability.

Complexity of Building Representation in One Version: Simplifying the representation of complex building geometries into a single model (called ‘version’ in Automodel), rather than requiring the creation of multiple versions, would prevent double counting of areas and improve the user comprehensibility of the model.

Checkboxes for Specific Design Considerations:

A checkbox for hillside locations, accounting for basement walls, could enhance the tool's accuracy in such scenarios.

Including a checkbox for acoustic level considerations would allow for the incorporation of additional sound-insulating measures like system ceilings and facing shells.

Providing checkboxes for different insulation levels for the building envelope could offer designers the ability to explore various insulation strategies.

Graphical Representation of Generated Early-Phase Model: Enhancing the graphical representation of the generated early-phase model would facilitate visualization and understanding, aiding designers in making informed decisions.

User-Friendly Component Switching: Incorporating a user-friendly switch to navigate between different components would empower designers to explore the impacts of diverse design decisions and identify optimal solutions.

Separate Parameters for Typology and Predefined Component Template: Separate specifications for the building function, i.e., type of use, and the component catalogue templates, i.e., the materiality of the building structure, would improve precision in representing the building and its intended use, acknowledging that these parameters contribute differently to the overall environmental impacts.

Uncertainty Range for Calculation Results: Introducing an uncertainty range for calculation results would provide users with a better understanding of the potential variability in outcomes, helping them interpret the significance of the results and adjust their design decisions accordingly.

In conclusion, the improvement suggestions outlined above, offer a pathway for enhancing Reduzer's Automodel as a robust tool for sustainable building design. By addressing these aspects, the tool could better cater to the needs of designers and enable them to make well-informed decisions in the early-phases of design, ultimately contributing to more environmentally conscious building practices.

7 Outlook

The preceding investigation has illuminated critical insight into early-phase GHG emission prediction of building designs, shedding light on the accuracy of GWP calculations of parametric modelled designs and their potential to inform design decisions at an early stage. While the current study marks a significant advancement, several avenues for further exploration and refinement emerge on the horizon. The following exemplary points delineate some key directions for further research:

To fortify the reliability and generalizability of the findings, it is imperative to engage in a broader spectrum of case studies. These new cases should encompass projects of comparable sizes and typologies. This will also allow parametric derivations such as the calculation of the number of interior walls to be statistically proven or disproven. Additionally, exploring the distribution of construction types within e.g., internal walls will provide deeper insights into the nuances of GHG emissions associated with different materials and construction methods.

While the current study focused primarily on parametric predictions for interior walls, the exploration of additional parametric variables remains for future research. Expanding the parameters to other building elements - such as roofs, floors, and exterior walls - will provide a more comprehensive framework for early-phase LCA calculations.

An additional pivotal facet that warrants attention is the assessment of the impact of design decisions on the ‘ground and foundation’ elements of building projects. Can the GWP of these foundational components be extrapolated based on the proportion of total GWP and the project's size? This intriguing question beckons further investigation. Understanding the intricacies of how design choices influence ground and foundation emissions has the potential to contribute significantly to a more holistic understanding of the building's environmental footprint.

The development of national standard component catalogues emerges as an instrumental stride toward standardization and comparability in early-phase LCA. A comprehensive catalogue would streamline the process of assigning GHG emission values to various building elements, promoting consistency in assessments across projects. The creation of such catalogues could be a collaborative endeavor, involving industry experts, policymakers, and researchers, ultimately leading to more accurate, transparent, and robust LCA analyses.

In conclusion, while the current study has paved the way for a more nuanced understanding of early-phase LCA predictions and their implications for sustainable design decisions, the future holds a realm of possibilities for further refinement and advancement. By pursuing these outlined avenues of research, the field of building sustainability can continue to evolve, equipping stakeholders with powerful tools to create environmentally responsible and innovative designs.

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Appendix

A Input Parameters of the Basic Investigation

A.a Case Study 1 – Basic Early-Phase LCA

<table>
<tr><th colspan="2">Automodel by Reduzer</th><th>Carbon Designer 3D by OCL</th></tr>
<tr><td colspan="2">Template: Kontor (Office building)
Stories:
7 above ground; 1 below ground
Footprint:
2065 m² above ground; 2240 m² below ground
GFA:
14.455 m² above ground, 2240 m² below ground</td><td rowspan="2">Reference building:
Norwegian reference building (without Lavar-bonbetong data) v2022.1
Structural frame:
Column-beam system. Beams only in the shorter axis of the building (Norwegian reference building default)
Building type: Office building
GFA: 16695 m²
Calculation period: 50 years
Stories above ground: 7
Stories below ground unheated: 1</td></tr>
<tr><td>Roof</td><td>Roof type: flat
Roof thickness: 0,3 m (default)
Roof skirt length: 0,3 m (default)</td></tr>
<tr><td>Walls</td><td>Story height:
3,7 m above ground; 3,0 m below ground
WWR:
37,6 % above ground; 30 % below ground (default)
External doors:
11 above ground; 2 below ground (default); 2 m²/door (default)
External wall thickness: 0,3 m (default)
Internal wall thickness: 0,15 m (default)
Average room size: 20 m² (default)</td><td rowspan="4">Height: 26 m
Width: 127,5 m (default)
Depth: 18 m (default)
Internal floor height: 3,7 m
Maximum column spacing distance: 9 m (default)
Load-bearing internal walls: 16 %
GIFA: 15880 m² (default)
Floor thickness: 0,3 m (default)
Envelope thickness: 0,3 m (default)
Roof shape efficiency factor: 1 (default)</td></tr>
<tr><td>Slabs</td><td>Slab thickness: 0,3 m</td></tr>
<tr><td>Load-bearing</td><td>Percent of outer wall area is load bearing:
0 % above ground (default); 100 % below ground
Percent of inner wall area is load bearing:
16 % above ground; 0 % below ground (default)</td></tr>
<tr><td>Found.</td><td>Foundation slab thickness: 0,3 m
Depth to solid ground: 10 m</td></tr>
</table>

A.b Case Study 2 – Basic Early-Phase LCA

<table>
<tr><th></th><th>Automodel by Reduzer</th><th>Carbon Designer 3D by OCL</th></tr>
<tr><td colspan="2">Template: Småhus
Stories:
2 above ground; 0 below ground
Footprint:
82,5 m² above ground (automatic calculation)
GFA:
165 m² above ground (without carport)</td><td>Reference building:
Norwegian reference building (without Lavarbonbetong data) v2022.1
Structural frame:
Wooden column-beam system
Building type: One-dwelling building
GFA: 165 m² (without carport)
Calculation period: 50 years
Stories above ground: 2
Stories below ground unheated: 0</td></tr>
<tr><td>Roof</td><td>Roof type: gabled; 27° angle
Roof thickness: 0,3 m (default)
Roof skirt length: 0,3 m (default)</td><td rowspan="5">Height: 6 m
Width: 15,9 m (default)
Depth: 7,2 m (default)
Internal floor height: 3 m
Maximum column spacing distance: 9 m (default)
Load-bearing internal walls: 0% (default)
GIFA: 176,6 m² (default)
Floor thickness: 0,2 m
Envelope thickness: 0,3 m (default)
Roof shape efficiency factor: 1,12</td></tr>
<tr><td>Walls</td><td>Story height: 3 m
WWR: 11 % above ground
External doors:
2 above ground (default); 2 m²/door (default)
External wall thickness: 0,3 m (default)
Internal wall thickness: 0,15 m (default)
Average room size: 20 m² (default)</td></tr>
<tr><td>Slabs</td><td>Slab thickness: 0,2 m (default)</td></tr>
<tr><td>Load-bearing</td><td>Percent of outer wall area is load bearing:
0 % above ground (default);
Percent of inner wall area is load bearing:
0 % below ground (default)</td></tr>
<tr><td>Found.</td><td>Foundation slab thickness: 0,2 m (default)
Depth to solid ground 3 m</td></tr>
</table>

B Input Parameters of the Geometry Study

B.a Case Study 1 – Geometry Study

<table>
<tr><th colspan="2">Automodel by Reduzer</th><th>Carbon Designer 3D by OCL</th></tr>
<tr><td colspan="2">Template: Kontor (Office building); Uoppvarmet (kjeller)

Stories:
7 above ground; 1 below ground

Footprint:

2065 m^2 above ground; 2240 m^2 below ground
122,5 m x 16,9 m (a. g.); 231,5 m x 9,7 m (b. g.)

GFA:
14.455 m^2 above ground, 2240 m^2 below ground</td><td>Reference building:
Norwegian reference building (without Lavarbonbetong data) v2022.1

Structural frame:
Column-beam system. Beams only in the shorter axis of the building (Norwegian reference building default)

Building type: Office building

GFA: 16.695 m^2; 122,25 m x 17,07 m</td></tr>
<tr><td>Roof</td><td>Roof type: flat

Roof thickness: 0,3 m (default)

Roof skirt length: 0,3 m (default)</td><td>Calculation period: 50 years

Stories above ground: 7

Stories below ground unheated: 1</td></tr>
<tr><td>Walls</td><td>Story height:
3,7 m above ground; 3,0 m below ground

WWR:
37,6 % above ground; 30 % below ground (default)

External doors:
11 above ground; 2 below ground (default); 2 m^2/door (default)

External wall thickness: 0,3 m (default)

Internal wall thickness: 0,15 m (default)

Average room size: 20 m^2 (default)</td><td rowspan="4">Height: 26 m

Internal floor height: 3,7 m

Maximum column spacing distance: 9 m (default)

Load-bearing internal walls: 16 %

GIFA: 15880 m^2 (default)

Floor thickness: 0,3 m (default)

Envelope thickness: 0,3 m (default)

Roof shape efficiency factor: 1 (default)</td></tr>
<tr><td>Slabs</td><td>Slab thickness: 0,3 m</td></tr>
<tr><td>Load-bearing</td><td>Percent of outer wall area is load bearing:

0 % above ground (default); 100 % below ground

Percent of inner wall area is load bearing:

16 % above ground; 0 % below ground (default)</td></tr>
<tr><td>Found.</td><td>Foundation slab thickness: 0,3 m

Depth to solid ground: 10 m</td></tr>
</table>

B.b Case Study 2 – Geometry Study

<table>
<tr><th colspan="2">Automodel by Reduzer</th><th>Carbon Designer 3D by OCL</th></tr>
<tr><td colspan="2">Template: Småhus; shed: Småhus

Stories:
2 above ground; 0 below ground
1 above ground0; 0 below ground

Footprint:
9,5 m x 8,4 m; shed: 1,8 m x 2,9 m

GFA:
159,6 m² above ground; shed: 5,2 m² above ground</td><td>Reference building:
Norwegian reference building (without Lavarbonbetong data) v2022.1

Structural frame:
Wooden column-beam system

Building type: One-dwelling building

GFA: 165 m²; 13,7 m x 6,0 m

Calculation period: 50 years

Stories above ground: 2

Stories below ground unheated: 0</td></tr>
<tr><td>Roof</td><td>Roof type: gabled; 27° angle; shed: flat

Roof thickness: 0,3 m (default)

Roof skirt length: 0,3 m (default)</td><td rowspan="5">Height: 6 m

Width: 15,9 m (default)

Depth: 7,2 m (default)

Internal floor height: 3 m

Maximum column spacing distance: 9 m (default)

Load-bearing internal walls: 0% (default)

GIFA: 176,6 m² (default)

Floor thickness: 0,2 m

Envelope thickness: 0,3 m (default)

Roof shape efficiency factor: 1,12</td></tr>
<tr><td>Walls</td><td>Story height: 3 m

WWR: 11 % above ground

External doors:
2 above ground (default); 2 m²/door (default)

External wall thickness: 0,3 m (default)

Internal wall thickness: 0,15 m (default)

Average room size: 20 m² (default)

Shared wall: 5,4 m²</td></tr>
<tr><td>Slabs</td><td>Slab thickness: 0,2 m (default)</td></tr>
<tr><td>Load-bearing</td><td>Percent of outer wall area is load bearing:

0 % above ground (default);

Percent of inner wall area is load bearing:

0 % below ground (default)</td></tr>
<tr><td>Found.</td><td>Foundation slab thickness: 0,2 m (default)

Depth to solid ground 3 m</td></tr>
</table>

Affidavit

I hereby certify that I have written this Master's thesis independently without the help of third parties and without using any sources or aids other than those indicated. I have indicated all passages in the thesis that are taken from printed works or sources from the Internet, either in wording or in meaning, by citing the sources. This also applies to all illustrations. The submitted work has not been the subject of any other examination procedure, neither in its entirety nor in essential parts. I am aware that plagiarism is serious academic misconduct that will be reported to the examination board and will result in sanctions. Furthermore, I assure that the electronic version of the Master's thesis corresponds to the printed version.

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Kufstein, 18.08.2023 Theresa Sophie Reif

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