Technische Universität München
TUM School of Engineering and Design

An Economic-Ecological Life Cycle Perspective for the Building Design Process

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Vollständiger Abdruck der von der TUM School of Engineering and Design der Technischen Universität München zur Erlangung einer

Doktorin der Ingenieurwissenschaften (Dr.-Ing.)

genehmigten Dissertation.

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Die Dissertation wurde am 28.06.2022 bei der Technischen Universität München eingereicht und durch die TUM School of Engineering and Design am 29.09.2022 angenommen.

Acknowledgements

At the end of this long, challenging, and exciting journey, I would like to express my sincere gratitude to all my travel companions. Thank you, Werner Lang, that you gave me the opportunity to pursue this topic at your institute that you shape with your enthusiastic spirit. Your continuous encouragement and the many interesting discussions about the value of sustainable building and the importance of the life cycle made this project enjoyable and certainly improved it. Thank you, Konrad Nübel, for agreeing to co-supervise this thesis and discuss the economic side of sustainability. Thank you, Frank Petzold, for agreeing to chair the committee. Thank you to the many colleagues at the TUM, who lend me their ears and provided their input. A special thanks goes to the colleagues and partners in the research projects that I had the privilege to be a part of, Design2Eco, wagnisART, EarlyBIM, Nachverdichtung, Lebenszyklusanalyse Tausendpfund, and the circularity indicator for the BNB system. Thank you to all my co-authors for your thoughts and contributions. Thank you to Michael Thon and the Tausendpfund group for providing detailed data on their FTMehrHaus. Thank you to my teaching partners, first and foremost Judith Schinabeck, who allowed me the first glimpses into the life cycle assessment world and was brave enough to team up with me although I virtually knew nothing about the topic. Last, but not least, the many students that I had the pleasure to teach, each provided something to this project in their own way. Thank you for sharing your thoughts, theories, and feedback. Thank you, Anne Winkelkotte, for your work on LCA and LCC, which provided the basis for a part of this dissertation. Thank you, Isa Nemeth, that you agreed to be the mentor for this dissertation, and for the many hours we spent on discussing sustainability, the end-of-life-of buildings, and life in general.

A dissertation is not only scientific work, but it also takes a lot of personal time and engagement. This would have not been possible without the support of my family and friends. Thank you to my brothers and my sisters in law, especially to Ansgar and Geli, for bearing with me and giving me room to complete this, despite the pressure from the construction site. Thank you, Leander, for your personal and scientific support in the publication processes, for proofreading my articles carefully and thoroughly. Thank you to my father, Roland Schneider, who always wanted to see me complete this higher degree and followed my progress closely and curiously as long as he lived. Thank you to my mother, for telling me not to give up and make sure to not hide my talents and supporting this journey. Above all, thank you to my husband Charles and my son Isidor for giving me space to pursue this and tolerating my highs and lows. Without your love and encouragement, this endeavour would have been impossible and certainly not as enjoyable.

Thank you!

Zusammenfassung

Lebenszyklusdenken (Life Cycle Thinking, LCT) in der Planungs- und Baubranche ist von entscheidender Bedeutung, um die Umweltauswirkungen und den Ressourcenverbrauch zu reduzieren, trotz der Herausforderung, komfortable Innenräume für die wachsende Weltbevölkerung zu schaffen. Die Ökobilanz (life cycle assessment, LCA) und die Lebenszykluskostenrechnung (life cycle costing, LCC) sind die entsprechenden ökologischen bzw. ökonomischen Berechnungsmethoden über den gesamten Lebenszyklus von Gebäuden. Diese Methoden können die Lebenszyklusqualität in unterschiedlicher Granularität aufzeigen, von der Bewertung der gesamten Lebenszyklusqualität ganzer Sektoren oder Länder bis hin zur Bereitstellung einer Grundlage für Entscheidungen im Bauplanungsprozess. Standardmäßige Bauplanungsprozesse beinhalten jedoch keine LCA oder LCC, es sei denn, es wird eine Nachhaltigkeitszertifizierung des jeweiligen Projektes angestrebt.

Von den unterschiedlichen Hindernissen, die einer breiteren Anwendung von LCA und LCC im Planungsprozess im Wege stehen, befasst sich diese Arbeit zunächst mit der Vielzahl von Indikatoren, die die Ökobilanz zum Ergebnis hat. Aufgrund der Komplexität der Umweltfaktoren können Ökobilanzergebnisse widersprüchliche Tendenzen aufweisen, ohne dass die Bedeutung eines Indikators gegenüber einem anderen erkennbar ist. Dies macht die Ergebnisse für Bauherren und andere Interessengruppen im Planungsprozess, die in der Regel keine Ökobilanz-Spezialisten sind, schwer verständlich. Obwohl Gewichtung und Normalisierung die Verständlichkeit und Nutzbarkeit der Ergebnisse in Entscheidungsprozessen der Gebäudeplanung verbessern, ist ihre Verwendung nicht üblich, obwohl verschiedene Gewichtungssysteme zur Verfügung stehen. Zwar ist die Gewichtung eine Wertentscheidung und sollte daher mit Vorsicht angewendet werden. Dennoch ist die monetäre Bewertung, d.h. die Umrechnung der Umweltauswirkungen in Währungseinheiten, eine vielversprechende Methode für den Einsatz im Planungsprozess. Sie bietet den Vorteil, dass sich die Ergebnisse in der gleichen Einheit zeigen wie wirtschaftliche Überlegungen, die bei der Planung von Gebäuden oft entscheidend sind. Die Anwendung minimaler und maximaler monetärer Werte auf die sogenannten Mid-Point Indikatoren, die derzeit in der Ökobilanz von Gebäuden in Deutschland verwendet werden, zeigt, dass die resultierende Gewichtung der Indikatoren unabhängig von den verwendeten Kostenwerten konsistent bleibt. Das Treibhauspotenzial ist demnach der entscheidende Indikator, ergänzt durch das Versauerungspotenzial und den abiotischen Ressourcenverbrauch.

Um die Lebenszyklusperspektive auch in wirtschaftliche Überlegungen einzubringen, erweitert LCC die Kostenperspektive von den kurzfristigen Investitionskosten auf die Folgekosten für den gesamten Lebenszyklus des Gebäudes. Sowohl LCA als auch LCC finden zunehmend Anwendung in der gebauten Umwelt, doch sind die beiden Methoden trotz ihrer Ähnlichkeiten nicht harmonisiert. Dies zeigt sich unter Anderem darin, dass es in der bisherigen Forschung an Transparenz hinsichtlich der verwendeten Methoden und Systemgrenzen mangelt. Aufgrund der Komplexität einer parallelen ökologischen und ökonomischen Bewertung werden in der Regel nur sehr begrenzte projektspezifische Fragen behandelt. Die Kombination von LCA, der monetären Bewertung von Umweltwirkungen und LCC hat jedoch das Potenzial, Treiber von Umweltkosten und finanziellen Kosten

im Lebenszyklus und den Zeitpunkt ihres Auftretens aufzuzeigen. "Eco^2" steht für diese harmonisierte Methode, die sowohl LCA als auch LCC umfasst. Die in dieser Arbeit entwickelte Eco^2-Methode verwendet ein gemeinsames Lebenszyklusinventar und harmonisiert die Systemgrenzen, um den zeitlichen Verlauf der Umweltkosten und finanziellen Kosten während des gesamten Lebenszyklus eines Gebäudes aufzuzeigen. Die Anwendung dieser Methode auf die Entwurfsvarianten einer Fallstudie zeigt Synergien - Möglichkeiten zur gleichzeitigen Einsparung von Umweltkosten und finanziellen Kosten - und Chancen für wirtschaftlich effiziente Emissionseinsparungen auf. Die Analyse zeigt, dass das Verhältnis zwischen Umweltkosten und finanziellen Kosten nicht nur von der Bewertung der Umweltkosten abhängt, sondern auch von den Teilsystemen des Gebäudes und zeitlichen Faktoren wie Diskontierung und Preisänderung. Bei der Konstruktion bleiben die Umweltkosten unter den meisten Umständen während des gesamten Lebenszyklus des Gebäudes unter den finanziellen Kosten, während die Umweltkosten in Verbindung mit dem betrieblichen Energieverbrauch schnell die finanziellen Kosten für die Gebäudetechnik übersteigen.

Zusätzlich erlaubt es Eco^2, zeitliche Aspekte in die LCA einfließen zu lassen, indem Diskontierung und Preisänderungen aufzeigen, wie und ob die Auswirkungen von Emissionen vom Zeitpunkt ihres Auftretens abhängig sind. Eco^2 trägt so zur aktuellen Diskussion um die Entsorgungsphase von Gebäuden bei und zur Frage, wie LCA den Effekt der Verzögerung von Emissionen aufzeigen kann. Die Diskontierung von Umweltkosten unterstützt das Verzögern von Emissionen, während eine Kostensteigerung der Umweltkosten zukünftige Emissionen als hochrelevant darstellt. Die Anwendung an einem Beispielprojekt zeigt auf, dass die Wahl dieser Parameter potenziell die Entscheidungsfindung stark beeinflussen kann.

Derzeit ist Eco^2 für spätere Planungsphasen geeignet, wenn Informationen über Materialien und gebäudetechnische Systeme des zukünftigen Gebäudes weitestgehend zur Verfügung stehen. Zukünftige Entwicklungsmöglichkeiten bestehen in der Anwendung von erweiterten Sensitivitätsanalysen. Dieses Projekt beinhaltet bereits eine Sensitivitätsanalyse für die Berechnung von Treibhausgasemissionen der Gebäudekonstruktion. Darüber hinaus bietet die Wissensdatenbank für frühe Planungsphasen, die in diesem Projekt für Ökobilanzdaten entwickelt wurde, die Möglichkeit einer Erweiterung durch die hier zusammengestellten projektspezifischen ökologisch-ökonomischen Daten. Dadurch werden ökologisch-ökonomische Ergebnisse verständlicher und nutzbarer für nicht-Spezialisten und zusätzlich robuster, so dass sie die wertvollen Informationen weiter verbessern, die Eco^2 für den Planungsprozess bereitstellt.

Abstract

Life cycle thinking (LCT) in the architecture, engineering, and construction (AEC) sector is vital for reducing the sector's environmental impacts and resource consumption while facing the challenge of creating comfortable indoor environments for the world's growing population. Life cycle analysis (LCA) and life cycle costing (LCC) are the relevant environmental and economic methods in LCT respectively. They prove useful on different levels of granularity, from evaluating the overall life cycle quality of entire sectors or countries to providing a basis for decisions in the building design process. However, standard building design processes do not include LCA or LCC, unless building sustainability certification is aimed at.

Of the multifaceted obstacles to the wider use of LCA and LCC in the design process, this work addresses firstly the multitude of indicators involved in LCA calculations. Because of the complexity of environmental factors, LCA results can display contradictory tendencies without an indication of the importance of one indicator over another. This makes results hard to comprehend to non-expert stakeholders in the AEC sector. Although weighting and normalizing results help to improve intelligibility and usability in the decision processes of building design, their use is not common despite the availability of several weighting systems. While acknowledging the fact that weighting is a value choice and hence should be applied with caution, monetary valuation, i.e., the conversion of environmental impacts into currency units, is a promising method for use in the design process. It offers the advantage to show results in the same unit as economic considerations, which are often decisive in building design. Applying minimum and maximum monetary values to the mid-point indicators currently used in building LCA in Germany shows that the resulting weighting of indicators stays consistent regardless of the cost values used. Global Warming Potential is the decisive indicator, complemented by Acidification Potential and Abiotic Resource Depletion (Elements).

To introduce a life cycle perspective into economic considerations, too, LCC extends the cost perspective from short-term investment cost to include follow-up costs for the entire life cycle of the building. The use of both LCA and LCC has seen increasing application to the built environment, but the two methods are not harmonized despite their similarities. Previous research lacks transparency regarding the methods and system boundaries used and tends to tackle very limited project-specific questions due to the complexity of a parallel environmental and economic evaluation. However, combining LCC with the monetary valuation of emissions has the potential to reveal drivers of environmental and financial cost and their points in time in the life cycle. "Eco^2" stands for this harmonized method including both LCA and LCC. The Eco^2 method developed in this thesis uses a common life cycle inventory and harmonizes system boundaries to result in a timeline showing the development of environmental and financial cost throughout the life cycle of a building. Applying this to the design variations of a case study reveals synergies - possibilities to save environmental and financial cost at the same time - and chances for economically efficient emissions saving. This analysis shows that the ratio between environmental cost and financial cost depends not only on the valuation of environmental cost, but also on the building sub-system and temporal factors, such as discounting and price change. For the building structure and finishes, the environmental cost stays below the financial cost under most circumstances throughout the building life cycle, whereas

the environmental cost quickly exceeds the financial cost of the buildings mechanical, electrical and plumbing (MEP) systems in conjunction with the operational energy use.

Additionally, Eco^2 allows introducing temporal aspects into LCA via discounting and price change to account for the time-dependency of the environmental effects of emissions. Eco^2 hence contributes to the current discussion about the end-of-life phase of buildings, and the question of how LCA can visualize the effect of delaying emissions. Using a discount rate for environmental cost favours delaying emissions, while assuming environmental cost increase causes future emissions to become highly significant. The potentially decisive effect of this on decision-making is illustrated by a sample project.

Eco^2 is currently applicable to advanced design stages, when information regarding the future building, its materials and systems, is available. Further development opportunities include the integration of sensitivity analyses. Sensitivity analysis has been applied within this project for greenhouse gas accounting of a limited system boundary of the building's structure and finishes. For early design stages, the knowledge database currently only developed for environmental data should be combined with the limited environmental-economic database established in this project and extended by more building parts and materials. As such, environmental and economic results would become more accessible to the non-expert and more robust, further improving the valuable information Eco^2 provides for decision-making in the building design process.

Abbreviations

ADPE	Abiotic Depletion Potential - Elements (for non-Fossil Resources)
ADPF	Abiotic Depletion Potential for Fossil Resources
AEC	Architecture, Engineering and Construction
AP	Acidification Potential (of Land and Water)
BBSR	Bundesinstitut für Bau-, Stadt- und Raumforschung (Federal Institute for Research on Building, Urban Affairs and Spatial Development)
BiRn	Bau-Institut für Ressourceneffizientes und Nachhaltiges Bauen GmbH (Building Insitute for resource efficient and sustainable building)
BNB	Bewertungssystem Nachhaltiges Bauen (Sustainability Certification System for Public Buildings)
BNK	Bewertungssystem Nachhaltiger Kleinwohnungsbau (Sustainability Certification System for Small Residential Buildings)
BMI	Bundesministerium des Innern, für Bau und Heimat (Federal Ministry of the Interior, Building and Community)
BMUB	Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit (Federal Ministry for the Environment, Nature Conservation and Nuclear Safety)
CML	Centrum voor Milieuwetenschappen (Institute of Environmental Sciences) Leiden
DGNB	Deutsche Gesellschaft für Nachhaltiges Bauen (German Sustainable Building Council)
EC	Environmental Cost
ELU	Environmental Load Unit
EP	Eutrophication Potential
EPD	Environmental Product Declaration
eq	Equivalent
gha	Global Hectare
GWP	Global Warming Potential
HVAC	Heating, Ventilation, Air Conditioning
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MEP	Mechanical, Electrical, Plumbing
NKW	Nachhaltiger Kleinwohnungsbau (Sustainable Small Residential Construction)
NPC	Net Present Cost
NPV	Net Present Value
ODP	Ozone Depletion Potential (Depletion potential of the stratospheric ozone layer)
PEF	Product Environmental Footprint
POCP	Photochemical Ozone Creation Potential
POP	Persistent Organic Pollutants
PCR	Product Category Rule
ReCiPe	RIVM (Rijksinstituut voor Volksgezondheid en Milieu) and Radboud University, CML, PRé Consultants; Method for impact assessment
UBP	Umweltbelastungspunkte (Environmental Load Points)
VOC	Volatile Organic Compounds

Content

1 Introduction

The attempt to apply life cycle assessment (LCA) during the building design process led to the idea of this thesis. I have been teaching architectural studio projects and the related seminar „application of a life cycle assessment“ during my time at the Institute of Energy Efficient and Sustainable Design and Building at TUM (Technische Universität München). The questions that arose during the intensive interdisciplinary design work with students, in conjunction with applied research projects (Lang & Schneider, 2017), are the seeds for this research. Firstly, in early design phases, we are looking for methods to estimate the environmental quality of buildings to compare alternative design solutions. What exactly does „environmental quality“ entail? is the question immediately following. Anyone concerned with the building design and construction process who is seeking the most environmentally friendly solution quickly faces this challenge. Hence, the design process needs guidance on the question which of the multitude of environmental indicators to prioritize and how to weigh these indicators, to arrive, ideally, at an unequivocal basis for decisions, i.e., a ranking of alternative designs. In addition, environmental quality is by far not the only decision criterion in the design process. Above all, economic criteria often prove to be decisive. The integration of life cycle cost (LCC) assessment is a promising method that helps to identify economically viable solutions. This dissertation project, therefore, aims to integrate both life cycle approaches (LCA and LCC) and thereby to facilitate their applicability to the building design process.

1.1 Background and Motivation

As buildings are responsible for a large share of greenhouse gas emissions (International Energy Agency [IEA], 2019) and resource consumption (Hegger et al., 2012; Herczeg et al., 2014), it is vital to find ways to drastically reduce building-related impacts. Reduction efforts in recent decades have focused on the operational phase, because building operation with the related energy consumption is responsible for the larger share (28%) of global greenhouse gas emissions, in comparison to the embedded emissions (11%) (IEA, 2019). However, with increasing energy efficiency and the use of renewable energy sources, life cycle phases with embedded emissions are gaining importance. In light of this, the current way of adopting a limited perspective when planning and designing the built environment, e.g., considering energy consumption for building operation only, will not enable stakeholders to respond to this challenge. On the contrary, a new way of design-thinking is necessary which includes all building-related disciplines in the design process and considers the entire life cycle of the building, including the manufacturing of building products, building operation, and construction and end-of-life processes. Only this interdisciplinary life cycle perspective avoids shifting burdens and enables the identification and realization of net-positive effects.

In this context, life cycle assessment (LCA) evaluates the environmental quality of buildings. At the same time, buildings do not only provide us with comfortable environments to live and work in, but they are also a major economic factor (Hillebrandt, 2000; Kohler & Moffat, 2003). Hence, for investors and planners, building costs are one of the decisive criteria in the building design process. For this perspective, too, a life cycle approach is important, to avoid shifting costs between life cycle phases and identify and quantify improvement potential over the entire life cycle. Life cycle costing (LCC) adopts this perspective and, like LCA, is currently gaining importance in the architecture, engineering, and construction (AEC) sector. Therefore, this study proposes an Eco² approach, considering LCA and LCC in a harmonized way.

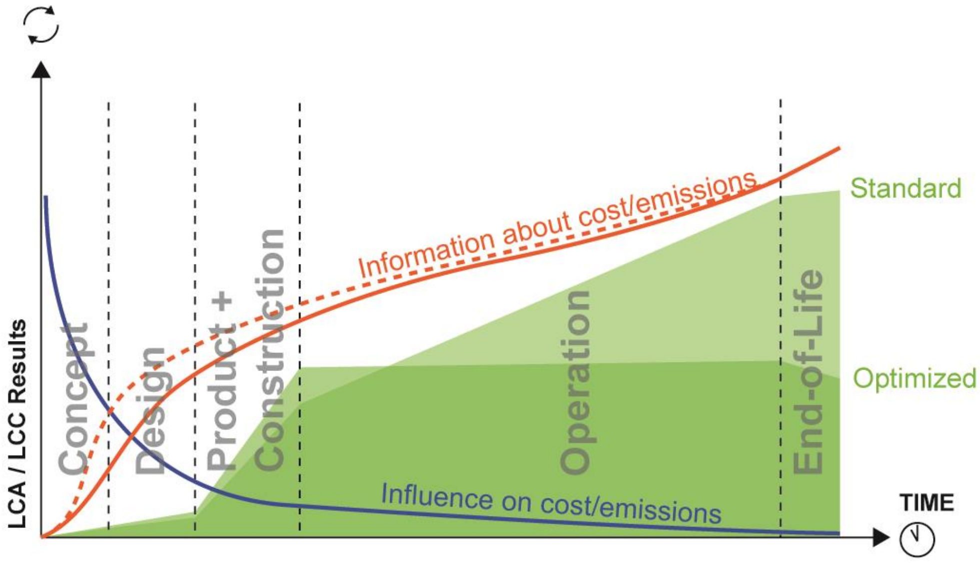

Figure 1: LCA and LCC in the building life cycle. The dashed line represents information in an LCA and LCC led design process.

With every decision, the building design process provides planners, designers, and decision-makers with opportunities to improve the life cycle performance of buildings. However, the significance of a particular decision for the building performance is rarely quantified. In parallel, calculations in early design phases are subject to many uncertainties, although changes can be implemented quickly and at a low cost at that point in the design process. These calculations become increasingly accurate during the design process (Figure 1), while changes become more difficult and costly to realize. Conducting LCA and LCC investigations during the design process as early as possible helps to shift information regarding life cycle costs and environmental impacts to earlier phases when improvement opportunities are greatest. Information provided early on often stems from later stages of as-built or as-designed building projects. As such, some of the investigations of this thesis are conducted when knowledge about buildings was already available.

Both LCA and LCC are part of the concept of life cycle thinking (LCT). LCT has found its way into policy in EU regulations as a basic concept introducing sustainability considerations and provide decision support. Although it is particularly suitable for the AEC sector, where longevity and the will to create structures to last for generations are inherent, the sector lags behind other sectors (e.g., household goods) in terms of implementing life cycle concepts (Sala et al., 2021). The methods corresponding to the three areas of protection of sustainability - environment, economy, society - life cycle assessment (LCA), life cycle costing (LCC), and social LCA (SLCA) have found limited, but increasing application in the AEC sector. At the same time, the fact that life cycle studies provide multi-layered answers to seemingly simple questions is both a joy and a pain. LCA as a method is manifold and can be extremely complex at the elementary flow level – oftentimes hundreds of elementary flows are analysed. At the same time, it is the only method promising a comprehensive evaluation of environmental quality. Starting with the analysis of packaging in the 1970s (Klöpffer,

2014) it has spread to many sectors and is used for several purposes at different levels of aggregation: from improving product and process quality to providing a basis for policy making. Research regarding LCA hence spans from basic research, e.g., the analysis of emissions at a molecular level, to applied projects, e.g., the implications of the environmental impact of entire sectors of the economy on a global level. This project aims at contributing to the practical applicability of life cycle thinking in the architecture, engineering, and construction (AEC) sector, by diving into the details of building LCA, combining them with economic considerations, and thereby making results more accessible and meaningful to stakeholders.

1.2 Purpose and Goals

The main purpose of this dissertation project is the improvement of the application of life cycle thinking in building design by harmonizing environmental (LCA) and economic (LCC) assessment. Table 1 illustrates the related goals pursued in the publications of this dissertation. As monetary valuation bears the opportunity for LCA and LCC result integration, a detailed study revealed its ability to weigh and summarize environmental impacts in building design (Schneider-Marin & Lang, 2020). Subsequently, a broad literature study was conducted revealing gaps and opportunities (Schneider-Marin et al., 2022a). From this, a framework was developed and applied to a case study (Schneider-Marin & Lang, 2022).

This project aims at contributing to making LCA fit for use in design processes. It investigates ways to reduce the multitude of indicators displaying contradictory tendencies to one or very few single indicators. While maintaining the depth of the analysis, the goal is to make LCA results more accessible to stakeholders. At the same time, a reduced set of indicators can provide a counterweight to the importance of economic factors in decision-making.

In the process, answers to the following questions are sought:

1. How can environmental and economic factors be integrated into building design?
2. Does monetary valuation provide a consistent weighting of building LCA results? If so, which environmental indicators are relevant for buildings according to monetary valuation?
3. What is the relationship between environmental and economic impacts of buildings?
4. (How) can building LCA include temporal factors in parallel to LCC?

Two secondary studies concern the application of LCA in early design phases: A sensitivity analysis showed potential strategic factors for early design emissions reduction (Schneider-Marin et al., 2020). Ecological data was re-structured and enhanced to better reflect material uncertainties in early design LCA and to make it more accessible to the non-expert (Schneider-Marin et al., 2022b).

Table 1: Goals and methods

Goal	Method	Application	Publication Nr.
Quantify early design LCA uncertainty	BIM-based parametric LCA: sensitivity analysis	Tausendpfund office building, (structure and finishes): construction material and energy standard variation	4
Increase usability of LCA data in early design	Structuring knowledge for LCA database development	EarlyData tool Tausendpfund office building	5
Investigate LCA and LCC in the AEC sector	LCA and LCC: Literature study	Eco^2 framework	2
Test monetary valuation in building LCA	LCA and monetary valuation: Variant study	Six office buildings	1
Apply harmonised LCA and LCC in building design	LCA, LCC, temporal factors: Variant study	Tausendpfund office building (complete): construction material and energy supply variation	3

The available information regarding a future building in the early design phases is incomplete and uncertain. Using a parameter-based and simplified calculation approach, a sensitivity analysis shows relevant parameters to guide designers both in the detailing process as well as showing environmental improvement potential (Schneider-Marin et al., 2020). Life cycle assessment in building design offers a great opportunity to positively influence the entire life cycle of the building already in the design process. At present, however, life cycle assessments are only carried out for comparative studies and in the context of sustainability certifications; they have not yet become an element of common design practice. One reason for this is that very precise material information for the building must be provided for the calculation, which is not available at an early stage of the building design. To alleviate this, a knowledge database is developed enabling early-design LCA on the basis of typical design information at an early point in the design process (Schneider-Marin et al., 2022b). A second reason for the absence of LCAs in the design process is the complexity and contradictoriness of the results described above, which, unfiltered, cannot be used as a basis for decision-making. The present project aims to improve usability of LCA for the design process of everyday projects by combining and presenting environmental criteria.

Because of their high energy and resource consumption, buildings cause various types of emissions during their life cycle. In turn, emissions affect the environment. Currently, global warming potential (GWP) is the most discussed environmental impact. Other impacts quantified by LCA calculations include Acidification, Eutrophication, Photochemical Ozone Creation, Ozone Depletion and Abiotic non-fossil Resource Depletion. In general, LCA results can contain information regarding life cycle inventory (LCI) indicators (e.g., primary energy (PE) consumption), emissions (e.g.,

NO_x emissions), mid-point indicators (e.g., Global Warming Potential (GWP)) and/or end-point indicators (e.g., damage to human health). This multitude of indicators makes the results hard to understand for non-experts and hence does not provide a sound basis for decisions. Moreover, complex LCA results do not provide a „counterweight“ to economic indicators that can be represented by one or a few readily understood figures. Therefore, the question of weighting the environmental indicators proves important as well as the effort to condense all indicators to a manageable number of results (Kägi et al., 2016). In this study, monetary valuation is evaluated as a weighting system, a way to combine indicators, and as a counterpart to LCC results. Thereby, relevant indicators are identified, and a range of monetary weights are assigned to the currently commonly used indicators in Germany (Schneider-Marin & Lang, 2020).

During the building design process, a life cycle perspective should be adopted to achieve long-term economic and environmental improvement. Lessons learned from an LCC approach can be applied to the LCA method: Within a budget, options are compared, and decisions involve trade-off discussions. Here, too, a life cycle perspective is necessary to pick the best long-term option. International standards developed for both building LCA (see sections 2.1.1 and 2.1.2) and LCC (see sections 2.2.1 and 2.2.2) define the general framework, such as the definition of the respective methods or building life cycle phases, but do not provide detailed guidelines on calculations. Therefore, the study develops a harmonized approach (see section 3), synchronizing life cycle phases, aligning system boundaries and cross-using underlying ideas, such as the time horizon introduced into LCC by price increases and discounting. As such, LCA and LCC methods achieve Eco² results (Schneider-Marin et al., 2022a). Additionally, a representation of results is proposed, revealing the evolution of environmental and economic factors throughout the building’s life cycle. The study results in a framework for harmonized application of LCA and LCC in the design process to provide a decision basis for stakeholders. A case study illustrates the application of the framework and investigates the implications of temporal parameters for design choices.

1.3 Research Structure

This dissertation project is based on three core publications, progressing both in breadth and depth of life cycle considerations in building design (Figure 2). As the initial idea came from experiences with LCA in building design, the first study applied monetary valuation to LCA results for weighting purposes. When juxtaposing these results to financial calculations, misalignment in the methods LCA and LCC became apparent. Hence, the second and third study broadened the field by including the methodological background for LCC, seeking to harmonize both methods. Additionally, the system boundaries for the case study building were completed by including the building’s mechanical, electrical and plumbing (MEP) systems and its operation.

Two related studies provided input on strategic factors for building LCA. A sensitivity analysis revealed relevant building sub-systems, whereas a knowledge database showed the relevance of material decisions. Both informed the development of alternative designs for the variant study, which illustrates the application of the framework and investigates the implications of temporal parameters for design choices.

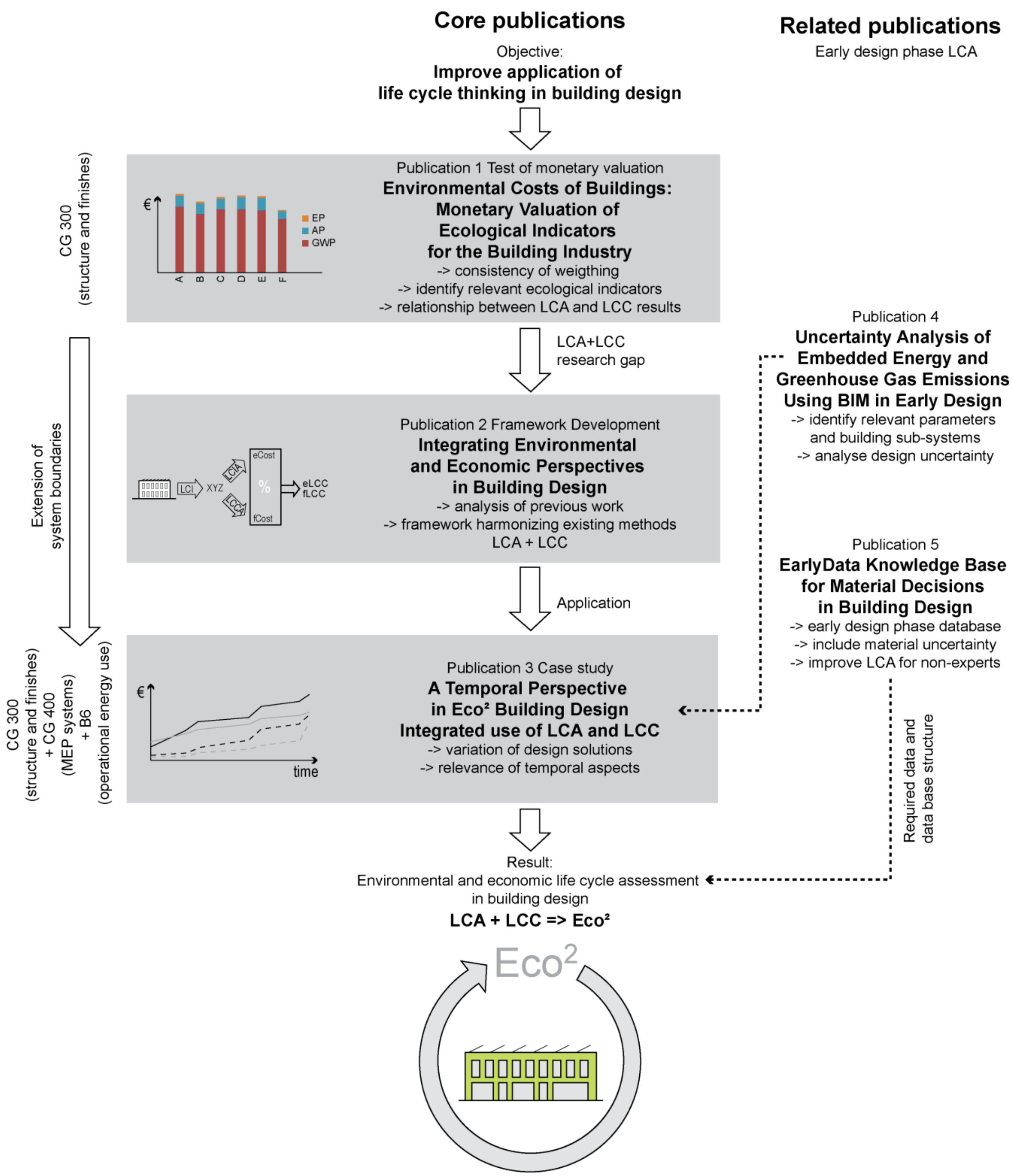

Figure 2: Structure of the project

The study results in a framework for harmonized application of LCA and LCC in the design process to provide a decision basis for stakeholders.

2 State of Current Research

Building life cycle assessments are currently almost exclusively carried out for research purposes or for building certification. They are not part of a standard design process. However, the scientific interest in building life cycle assessment has increased strongly in recent years (Bahramian & Yetilmezsoy, 2020) and continues to rise. This chapter sheds light on the state of current research in LCA, available weighting and normalization methods for LCA results, followed by the LCC methods and the integration of both LCA and LCC. Finally, uncertainties in the building design process are addressed.

2.1 Life Cycle Assessment (LCA)

2.1.1 The LCA Method

The LCA method was originally developed for the evaluation of products and the related production processes. It adopts a life cycle perspective to arrive at a complete assessment of environmental aspects and impacts of product systems. DIN EN ISO 14040 (first version published in 1997) and DIN EN ISO 14044 lay down the general framework for LCA. According to DIN EN ISO 14040, LCA consists of the phases Goal and Scope Definition, Inventory Analysis and Impact Assessment, with a continuously ongoing interpretation process (Figure 5, page 20).

Generally, two different approaches exist: top-down (input-output based) and bottom-up (process-based) LCA. In top-down LCA, economic input-output data is used to analyse material flows and environmental impacts for the entire economy and subsequently allocated to each sector. An advantage of this approach is that it is complete, i.e., it includes direct and indirect sectoral impacts, thereby not excluding any impacts because of cut-off or allocation decisions (Majeau-Bettez et al., 2011). The challenge inherent in this method is the disaggregation of data to arrive at product-specific values. Hence, data granularity is lower than in a process-based approach. Bottom-up (process-based) LCA analyses all processes and inputs required for a product or a service and calculates related inputs, outputs and emissions. This is the approach commonly used in building LCA in Germany. Its advantage is the possibility to distinguish between building products with high accurateness if data is available. Generally, input-output LCA results in higher emissions values than process-based LCA (Nässén et al., 2007; Säynäjoki et al., 2017).

Guidelines on the normalization, grouping and weighting of results, closely related to the subject of this thesis, are contained in current standards as optional elements of the life cycle impact assessment (LCIA) (see section 2.1.4). As the weighting of results is a value choice, the standard DIN EN 14044 prohibits weighting in studies for the public. However, to communicate LCA results to the layperson, weighting of the results is necessary to provide decision guidance (Roesch et al., 2020) and should be legitimate if choices are made transparent.

2.1.2 Building LCA

LCA is in the process of being established as the standard evaluation method for the environmental quality of buildings with steadily increasing research activity in the field (Saade et al., 2020; Sauer & Calmon, 2019). The development of standards related to building LCA confirms this trend: DIN

EN 15643-2 lays down general rules for environmental sustainability assessment for buildings. Based on this standard, DIN EN 15978 contains calculation rules for the evaluation of the environmental quality of buildings, while DIN EN 15804 is concerned with Environmental Product Declarations and stipulates the requirements for product category rules (PCR) for building products. None of these norms, however, specifies particular conventions or rules for building LCA, such as system boundaries, length of the study period or cut-off criteria. Hence, results of building LCAs lack comparability, aggravated by the fact that underlying data is not harmonized (Frischknecht et al., 2020; Mahler & Schneider, 2017).

The unique quality of life cycle assessment is the holistic perspective it adopts, a feature it has in common with LCC. Hence, the division of the life cycle of buildings into different sub-phases (Figure 6) is considered in parallel for LCA and LCC: For a detailed description of the life cycle phases used in LCA and a comparison with the life cycle phases used in LCC, see section 2.3.2.1.

Building LCA differs from consumer product LCA in several important aspects:

- Except for prefabricated standard buildings, buildings are unique, i.e. each building requires an individual LCA
- A building consists of a multitude of products rather than a limited number of ingredients and processes (Singh et al., 2011)
- Moreover, buildings are developed for one particular site, i.e. site-related processes (such as transport, construction) are non-standardized and need to be analysed with process data rather than product data
- Building life cycles are much longer than consumer product life cycles (Kohler & Moffat, 2003)

To reduce the complexity of building life cycle assessments, the common practice uses product data for the materials contained in the building. This data is either generic, average, or specific, i.e., taken from manufacturer's environmental product declarations (EPDs) (Gantner et al., 2018). This simplifies the calculation procedure as it avoids analysing each step in the production of building materials by using product-specific standard data. At the same time, this reflects current practice without showing potentials in production process improvements. For example, if the electricity mix changes towards more renewable technologies with fewer emissions, any building material using electricity for its production has more improvement potential than building products relying on the consumption of fossil fuels. However, the LCA contained in a building material manufacturer's EPD can be employed to illustrate the materials improvement potential and provide an incentive via competition amongst manufacturers. In addition to the EPD approach, the product environmental footprint (PEF) method initiated by the European Union provides similar yet more holistic information, e.g., containing more environmental indicators (Ecofys, 2014). Currently, the PEF approach exists in parallel to the EPD approach, necessitating a harmonization effort (Passer et al., 2015). As PEFs are a recent development while EPDs have been common practice in the AEC sector for some time, current building LCAs in Germany are based on EPDs of construction products. However, some elements of the PEF method can inform the EPD, as the PEF method aims to develop LCA further by harmonizing approaches and providing a comprehensive comparable assessment (Ecofys, 2014).

Building certification systems have established calculation rules to ensure comparability between results and provide a sound basis for evaluation. The LCA criterion in the BNB system (BMUB, 2015b) specifies, amongst other rules, a 50-year study period, the system boundaries (e.g., building parts, life cycle phases), environmental indicators to be included and benchmarks values for the same. The LCA criterion of the DGNB system (DGNB GmbH, 2018b) largely agrees with the BNB system. The two main differences are the inclusion of phase D in the calculations - BNB does not consider phase D in LCA results - and the quantification of benchmarks.

Although it is not part of a current design process unless sustainability certification is intended, LCA is increasingly recognized as a tool during the design process to improve the environmental quality of buildings. To align LCA with the design process, the European EEBGuide (Wittstock et al., 2012) defines a sequence of LCA types for the design process with increasing accuracy: screening LCA, simplified LCA, and complete LCA (see section 2.3.3).

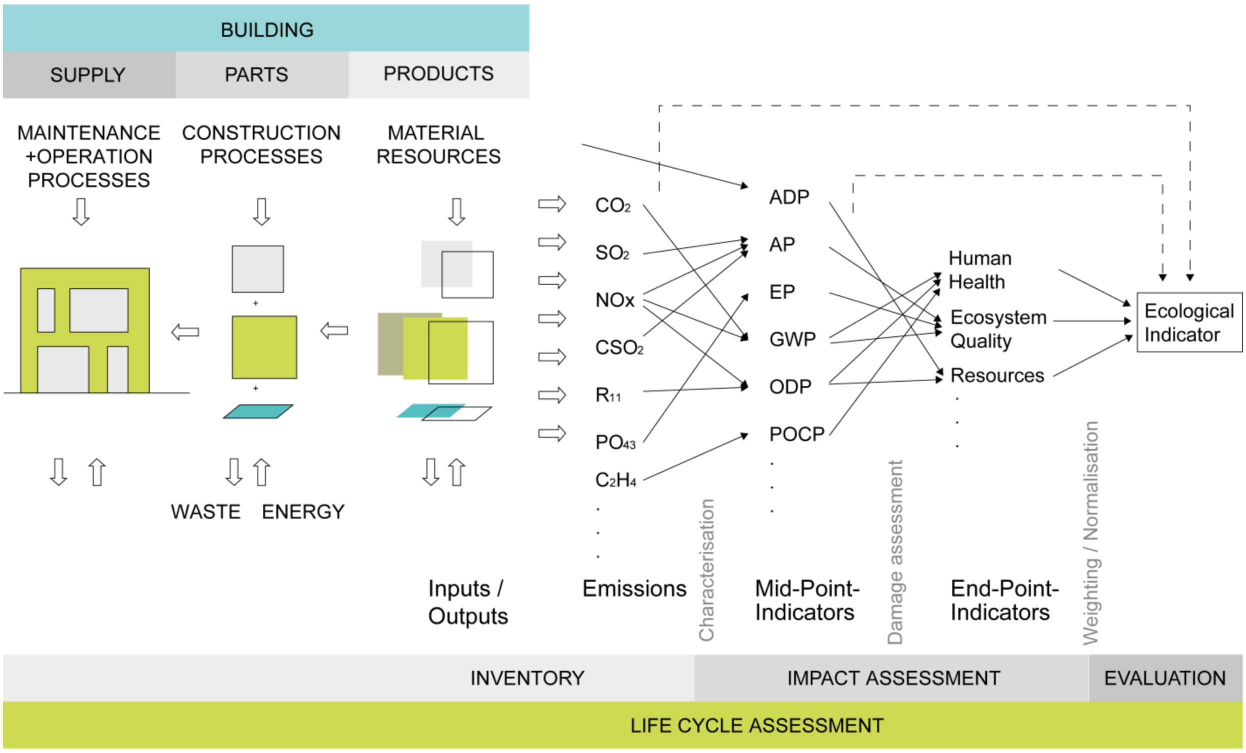

Figure 3 Building LCA process and LCIA methods. A similar representation was published in (Schneider-Marin & Lang, 2020).

2.1.3 LCA Results: Indicators

LCA displays several results. Firstly, the life cycle inventory (LCI) quantifies indicators for resource use - inputs and outputs (e.g., energy, waste) required to manufacture building materials and operate the building (Figure 3, Table 2). The related emissions are also part of the LCI. Subsequently, life cycle impact assessment (LCIA) evaluates the emissions resulting from the LCI in terms of their impact on human health, the natural environment, and issues related to natural resource use (EC JRC, 2010).

2.1.3.1 Life Cycle Inventory Indicators: Input-Output

Input categories quantify the flows crossing the system boundary to the building: primary energy (in MJ), secondary materials (in kg), secondary fuels (in MJ) and water (in m³). Output categories are waste (in kg), components for further use, recycling or energy generation (in kg), and exported energy (In MJ). (Table 2)

Table 2 Input and output categories per DIN EN 15643-2, DIN EN 15978, DIN EN 15804

	Category		unit
Input	PENRT	Total use of non-renewable primary energy	MJ
	PENRM	Non-renewable primary energy for material use	MJ
	PENRE	Non-renewable primary energy use	MJ
	PERT	Total use of renewable primary energy	MJ
	PERM	Renewable primary energy for material use	MJ
	PERE	Renewable primary energy use	MJ
	SM	Input of secondary material	kg
	RSF	Use of renewable secondary fuels	MJ
	NRSF	Use of non-renewable secondary fuels	MJ
	FW	Use of net fresh water	m³
Output	HWD	Hazardous Waste disposed	kg
	NHWD	Non-hazardous waste disposed	kg
	RWD	Radioactive waste disposed	kg
	CRU	Components for re-use	kg
	MFR	Materials for recycling	kg
	MER	Materials for energy recovery	kg
	EEE	Exported electrical energy	MJ
	EET	Exported thermal energy	MJ

Of these, standard building LCA calculations display primary energy values (non-renewable, renewable), broken down in the use of primary energy as fuel and primary energy resources used as raw materials. Other input/output indicators are rarely investigated although the Ökobaudat database contains the values for these. Life cycle inventory studies are useful, as they quantify the direct inputs and outputs of buildings and thus can give an indication of resource consumption. However, quantifying tens or hundreds of types of indicators and using them directly for the comparison of products is virtually impossible. Hence, inputs, outputs and emissions are grouped and their relative impact on different environmental problems is quantified in the next step: LCIA.

2.1.3.2 Life cycle Impact Assessment Indicators: Environmental Impacts

Several LCIA methods are available. Table 8 (Appendix A.1) shows the most common methods, differing in their spatial applicability and their purpose. For example, LIME (Itsubo & Inaba, 2012) applies to Japan, whereas LUCAS (Toffoletto et al., 2007) applies to the Canadian context. The choice of the LCIA method also depends on its application, be it the comparison of products and processes, environmental improvement, or policymaking.

There are two types of LCIA impact categories (Figure 3). Firstly, mid-point impacts show the contribution to an environmental problem. Of these, GWP (global warming potential) presently receives the highest amount of public attention, as the effects of global warming become perceivable with more extreme weather events and the melting of polar ice, requiring urgent change to prevent global catastrophe. Mid-point impacts are expressed in "potentials" and characterised with reference to a representative substance, i.e., in "equivalent".

Secondly, end-point impact categories combine either emissions directly or (mid-point) environmental problems via damage assessment to areas of protection (e.g., human health). Characterisation factors serve to convert emissions to impacts, either in relation to a reference substance or in relation to areas of protection. Notably, the number of emissions included in the LCIA, as well as characterization factors, differ between LCIA methods, as not all effects of emissions are known in detail. Characterization from emissions to mid-point indicators is generally more exact than conversion to end-points because uncertainties in linking emissions to environmental damage are lower than in linking environmental damage to their effect on human health, ecosystems or resource availability.

2.1.3.3 Environmental Indicators for Buildings

Table 3: Environmental impact categories per DIN EN 15643-2, DIN EN 15978, DIN EN 15804 and characterization per DIN EN 15804:2014-07

Environmental impact category	**unit**	**LCIA (characterization) per DIN EN 15804:2014-07[1]**
GWP	kg CO_2-eq.	(Solomon et al., 2007) (time horizon: 100 years)
ODP	kg CFC-11-eq.	(Ennis, 2002) (stationary state)
POCP	kg C_2H_4 eq.	(Derwent et al., 1998) (Jenkin & Hayman, 1999)
AP	kg SO_2 -eq.	(M. Huijbregts, 1999) (average European values)
EP	kg PO_4-eq.	(Guinée et al., 1992)
ADPF	MJ	(van Oers et al., 2002)
ADPE / ADPelem	kg Sb-eq.	(van Oers et al., 2002)

[1] DIN EN 15804:2020-03 has updated characterisation factors. The current Ökobaudat is based on the factors per DIN EN 15804:2014-07

Currently, standard building LCA in Germany shows the environmental impacts displayed in Table 3. DIN EN 15804, the basis for LCA calculations in EPDs, stipulates characterisation factors for building LCA in Germany. Although the latest version of the standard (DIN EN 15804:2020-03, appendix C) updates these factors, the Ökobaudat version (2021-II) used as a basis for this study, incorporates EPD data based on the previous version (DIN EN 15804:2014-07), i.e., the characterization methods listed in Table 3 still apply to this study.

DIN EN 15978 defines the impacts shown in Table 3 to be mandatory for buildings. Other optional indicators (per DIN EN 15804:2014-07) include toxicity to ecosystems (ETP) or humans (HTP), land use and land-use change (LULUC). The standard states that these impact categories lack an agreed-upon basis for standardization and are therefore not included in current calculations. It is striking that there is no indication as to which set of indicators might be relevant to the AEC sector, either because the AEC sector causes a large part of global impacts or because it is affected disproportionally by a related environmental issue. This is in part because LCA is not a methodology specific to the AEC sector, i.e., the impact categories are sufficiently defined due to their use for quite some time in product development. As this multitude of indicators adds complexity to the application of LCA in the AEC sector and makes results hard to comprehend to the layperson, previous studies have tried to identify relevant indicators for buildings hoping to reduce the number of indicators or even to be able to identify one single lead indicator.

Herczeg et al. (2014) qualify only three indicators as relevant for the AEC sector (operation excluded): a combined toxicity potential (TP), abiotic resource depletion potential (ADP), and global warming potential (GWP). Production data for materials used in the AEC sector is at the core of this analysis. Based on the ecoinvent 2.0 database, Lasvaux et al. (2016) identify a set of LCIA indicators for building materials that show no correlation. This means that they are representative for the overall environmental impact, but also that this is the minimum set of indicators to be considered to avoid gaps in the evaluation: Fossil fuel energy consumption, eco-toxicities (and human toxicity driven by water emissions), ionising radiation and ozone layer depletion, land use, and mineral resources depletion. Without indicating the overall relevance of the respective indicators, Silva et al. (2020) conclude that the following mid-points dominate environmental impacts of construction foreground processes: GWP, fine particulate matter formation (FPMF), ozone formation (human health and terrestrial ecosystems), terrestrial acidification, terrestrial ecotoxicity, land use, resource scarcity (fossil and mineral), and water consumption. This latest study relates to construction products in Brazil and uses the ReCiPe hierarchist method (see 2.1.4.3) for contribution analysis.

In contrast to such attempts to reduce the number of indicators, other studies recommend extending the set of indicators. Passer et al. (2015) show that toxicity, land use, biodiversity and resource usage are potentially important factors in building evaluation and recommend increasing data and working towards standardization to include them in building assessment.

2.1.4 Summarizing Environmental Indicators: Normalisation and Weighting

The interpretation of results is the fourth phase in the LCA process, finding answers to the questions posed in the goal and scope definition. In this phase, the findings from the inventory and/or the impact analysis are interpreted to arrive at conclusions and recommendations (DIN EN ISO 14040).

This iterative process might require further data acquisition or a more detailed disaggregation of results. Any LCA study asks the underlying question of which product or process is "good" or, at least, "better" than other choices. In building LCA, such comparisons can take place on a building product (or building-related process), building part, or building level. Life cycle interpretation, i.e., making results understandable as a basis for decisions is vital for applicability and implementation of LCA into construction practice.

Normalization, grouping and weighting (part of the LCIA) provide the basis for life cycle interpretation. However, DIN EN 14040 defines these elements to be optional. Moreover, DIN EN 14044 forbids weighting in "comparative assertions intended to be disclosed to the public" (DIN EN 14044, 4.4.5). Especially normalization and weighting are controversially discussed topics in the scientific community (Finnveden et al., 2002; Roesch et al., 2020, 2021; Sala et al., 2021). In normalization, the environmental impacts are set in relation to a reference value, e.g., global impacts or ecological carrying capacity (Roesch et al., 2020, 2021). Weighting subsequently assigns weights to each indicator result or normalized indicator result to arrive at a basis for comparison. Normalization and weighting are closely connected and can be contained in one single step (Steen, 2006).

The idea behind weighting is to summarize the environmental indicators from LCIA and arrive at unequivocal results either by displaying a single score or by ranking alternatives according to the weights assigned to indicator results. Weighting is subject to criticism for several reasons. First, it is a value choice, i.e., it is based on an individual's or organization's preference which environmental issue is the most pressing and potentially outweighs other issues (Bengtsson & Steen, 2000). Second, this value choice can involve trade-offs as it implies that good performance in one indicator compensates for worse performance in another. Therefore, it runs the danger of indicating a measure of weak sustainability only (Steen, 2006).

However, if used with caution, made explicit, and communicated transparently, weighting can be a powerful support to stakeholders in decision-making. Without normalization and weighting, LCA results might appear contradictory and arbitrary to a client or consultant, leading her/him to disregard the results, or to turn to other criteria than environmental aspects.

Building certification systems in Germany have assigned weights to environmental indicators, not only for LCA but also for many other sustainability criteria. The weights assigned to environmental impacts differ significantly (Table 4) between the different systems. The highest weight is consistently attributed to GWP, with equal lower weights for AP, EP, POCP and ODP. Only the latest DGNB version differentiates between these indicators and excludes ODP by assigning 0% weight to this indicator.

For normalization and subsequent weighting, benchmark values play an important role. These can be calculated either using a top-down or a bottom-up approach, or a combination of both (Hollberg et al., 2019).

Table 4 Weighting of LCA environmental indicators in German sustainability certification systems for buildings (amongst environmental impacts only, without primary energy (PE)) and overall weight of LCA and LCC criteria; NBV=new office and administration buildings, NKW=new small residential buildings, BNK=sustainable small residential buildings.

Sustainability certification system	GWP	AP	EP	POCP	ODP	Overall weight of LCA results (incl. PE)	Overall weight of LCC results
DGNB NBV 2013 (DGNB GmbH, 2013a)	40%	15%	15%	15%	15%	18%	11,3%
DGNB NBV 2015 (DGNB GmbH, 2015)	40%	15%	15%	15%	15%	13,5%	9,6%
DGNB 2018 (DGNB GmbH, 2018b) and 2020 (DGNB GmbH, 2020)	57,1%	14,3%	14,3%	14,3%	0%	9,5%	10%
DGNB NKW 2013 (DGNB GmbH, 2013b)	40%	15%	15%	15%	15%	7,8%	8,4%
BNB 2011 (BMUB, 2011)	42,9%	14,3%	14,3%	14,3%	14,3%	13,5%	13,5%
BNB 2015 (BMUB, 2015a)	42,9%	14,3%	14,3%	14,3%	14,3%	12,5%	11,25%
BNK (BiRn, 2015)	100%	0%	0%	0%	0%	7%	25%

2.1.4.1 Top-Down Evaluation

Top-down approaches derive benchmarks or target values from an overarching goal, e.g., staying within the carrying capacity of the earth, putting a limit to rising global temperatures (2-degree target) or maintaining resources for humankind. Prominent examples are the environmental footprint developed by Wackernagel in 1994 (Wackernagel, 1994) and the concept of the 2000-Watt-society (Blindenbacher et al., 2020). Benchmarks are the basis for normalisation and weighting, as they establish at the same time factors for normalisation and limits for distance-to-target weighting approaches.

An example of a weighting system based on top-down benchmarks is the ecological scarcity method. This method evaluates the distance to established policy targets and summarizes indicators using environmental load points (German: Umweltbelastungspunkte, UBP). Current, critical and normalization flows serve to establish eco-factors for climate change, water resources and acidification (Muhl et al., 2020). Ahbe (2014) derived eco-factors for Germany. Currently, these factors do not apply to standard building evaluation, as, except for GWP, they establish eco-factors for emissions in lieu of mid-point indicators. Hence, mandatory environmental mid-point impact categories (see section 2.1.3.3) are missing (Schneider-Marin et al., 2019).

The most important advantage of deriving benchmarks for buildings using a top-down approach is that it answers the general question about the overall environmental quality of the building (Hollberg et al., 2019). As such, a building receives an “emission budget” as a limit to its life cycle emissions. However, this approach has several drawbacks. While it might seem obvious to establish such an overall budget, allocation to different economic sectors (e.g., industry, energy) or activities (e.g., buildings) is more challenging, let alone to single buildings. Allocation depends on the overall emissions intensity of an activity as well as the possibility to reduce emissions within the sector, or the risk of increasing emissions due to growth. Additionally, a top-down approach does not readily reveal improvement opportunities of parts of economic sectors, e.g., in the case of buildings, building parts or building processes (Hollberg et al., 2019).

2.1.4.2 Bottom-up Evaluation

Bottom-up evaluation uses current practice to establish standard, minimum or target values. For the AEC sector, this can entail establishing typical or “standard” buildings, independent of geometry and specific conditions, resulting in “external” benchmarks. If large amounts of data about the materiality and operation of newly built buildings were available, true average benchmarks would be a possibility. An “internal” benchmark, on the other hand, employs a reference building, a copy of the building design in question, with standard building parts (Spirinckx et al., 2018). For building LCA, this method is not established in Germany, but for the evaluation of the energy performance, it has been in use since the energy efficiency ordinance of 2009 (Deutsche Bundesregierung, 2009).

Departing from bottom-up benchmarks using existing technologies, best practice or “best-in-class” target values can be defined. As such, targets are achievable and, if allocation to different building parts is transparent, can provide guidance in the design process. However, contrary to top-down benchmarks, no relation to overall environmental targets is visible.

Evaluation of LCA results in building sustainability certification systems in Germany is based on such a bottom-up approach. However, there is a lack of transparency regarding the origin of target values, making them difficult to use in the design process. Another example for the use of bottom-up benchmarks for normalization is the Austrian OI3 indicator (IBO GmbH, 2016). Here, benchmark values for three indicators, PENRT, GWP and AP, are calculated on a building-part and building level to establish the environmental evaluation. The corresponding calculation method does not give any explicit reason for the choice of the three indicators.

Typical functional units to make different buildings comparable with regard to a bottom-up benchmark are geometry-related, such as the usable area or building volume, or, more recently, user-focussed (e.g., an occupant, a workspace) (e.g., E. Hoxha et al., 2020a).

2.1.4.3 Single Point Methods

One single number summarizing LCA results and thereby identifying the ecologically “best” solution is the goal of single-point normalization and weighting methods. The most straightforward way to arrive at an unequivocal result is to define one indicator as the lead indicator. This would entail that, first, this indicator is decisive for the overall environmental quality (again, based on weighting) and, second, that all included indicators correlate without any trade-offs involved, i.e., a reduction in impact from one indicator does not increase a different type of environmental damage. A widely used single-point method is the use of carbon footprints, implying for example that “carbon neutral” is equivalent to “environmentally friendly”, or even “sustainable”. Considering the complete life cycle of buildings, Ströbele (2013) indicates that the carbon footprint is not sufficient to represent the environmental quality of buildings. At the minimum, building LCA should additionally account for acidification potential (AP).

If more than one indicator is to be considered, some kind of weighting needs to be applied to summarize indicators to one value. As illustrated in Figure 3, this process can take place from emissions to a single indicator directly or via mid-points or end-points, or a choice of two or three out of these different stages of LCIA. Aligning characterization and weighting methods in LCIA ensures consistent results. To be able to summarize mid-point or end-point indicators to one value, the indicators have to be equivalent and use the same unit as a measure.

In the Eco-indicator method (Goedkoop et al., 1996; Goedkoop & Spriensma, 2000), which has been further developed to the ReCiPe method, three alternative perspectives define mid-point and end-point weighting: „individualist“, „hierarchist“, und „egalitarian“ (Goedkoop et al., 2013). This implies differing time horizons with corresponding uncertainties. In more recent descriptions of the method (Huijbregts et al., 2016; Huijbregts et al., 2017), the naming of these perspectives has been omitted, but a variation in characterisation and weighting factors still applies. As several mid-point impacts necessary for ReCiPe evaluation are not included in DIN EN 15804 / DIN EN 15978, Ökobaudat does not display results in ReCiPe Points. Therefore, ReCiPe points are not common practice in building evaluation in Germany.

The environmental load points of the Swiss ecological scarcity method (see section 2.1.4.1) add up to a single-point indicator representing all included emissions and related environmental problems. The higher the number, the heavier the environmental load. Although this allows comparison between different product systems, it is not a readily understood figure. The lack of an established relation to the resulting numbers is a disadvantage and, at the same time, a benefit of such weighted point systems. Although it makes results hard to interpret, it allows for establishing benchmarks and makes it obvious that it deals with an exclusive framework incomparable to other values.

2.1.4.4 Monetary Valuation

Monetary valuation is a special sub-type of single-point methods. In contrast to the methods described in the previous section 2.1.4.3, the resulting unit is a familiar value, currency. Weighting between impact categories happens indirectly by the use of the same reference system. The resulting costs are known as external cost (Gibson et al., 2014; Kuika et al., 2017; Olba-Zięty et al., 2020), eco-cost (Vogtländer et al., 2001), environmental cost (Ghisellini et al., 2018; Liu, 2020; Tomsic, 2014), or shadow prices (Kee, 2005; Krieg et al., 2013). For this study, “environmental cost” is used as this term has the closest relation to the environmental concerns dealt with in LCA.

The available methods to convert emissions, mid-point or end-point indicators to monetary units are grouped into two differing underlying ideas. Firstly, prevention or abatement costs quantify the cost of measures to avoid environmental damage, and, secondly, damage costs value the damage to the environment. Intuitively, prevention costs should be lower than damage or repair costs, i.e. it is preferable to avoid damage than to compensate for the consequences of environmental problems.

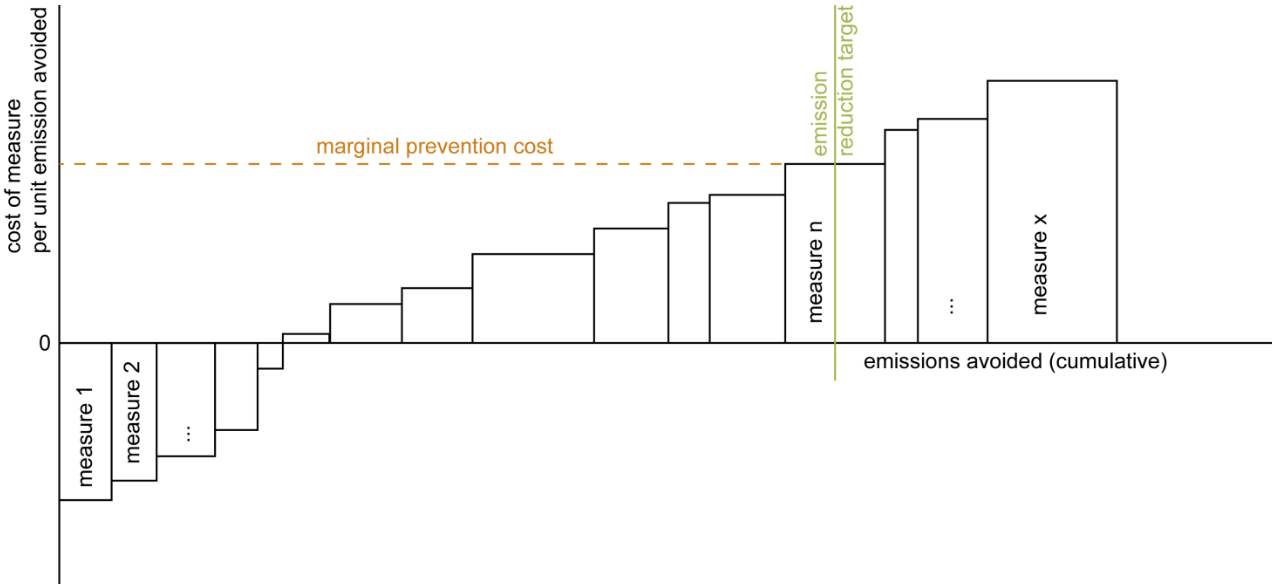

Figure 4 Marginal prevention cost

Figure 4 illustrates how marginal prevention cost is calculated. The underlying information needed is, first, the sustainable level of pollution, related to the ecological carrying capacity. This is a familiar top-down benchmark from normalisation and weighting (see section 2.1.4.1). Second, as the bottom-up part of this exercise, the question of available methods to prevent emissions arises and their potential for reducing emissions needs to be quantified. Third, economic evaluation determines the market cost of related measures. Marginal prevention cost is the cost of the most expensive measure needed to arrive at sustainable levels of pollution (Vogtländer & Bijma, 2000).

The method of abatement costs has reached some public attention. It is an intensely discussed topic for carbon pricing and the prevention of greenhouse gas emissions. For example, Mc Kinsey (2009) has been publishing CO_2 abatement cost curves identifying the global greenhouse gas prevention potential of measures at a cost below 60$ per ton of CO_2. In general, marginal prevention costs provide information on the investment required to reach an environmental target.

Damage-oriented monetary valuation assesses the potential damage to society. Hence, this approach overlaps with social LCA. It is based on the willingness to pay (WTP) for changes in environmental quality. As environmental quality is not a traded good, no market price for it is available, i.e. other than market mechanisms determine its (economic) value. Table 5 shows the different WTP approaches currently in use. Some of these approaches (e.g., political WTP) overlap with prevention costs, as they use prevention costs to determine the willingness to pay.

Publication 1 (Schneider-Marin & Lang, 2020) contains a list of monetary valuation models, included indicators and related valuation methods as a basis for an analysis of the effect of minimum / maximum valuation on building LCA weighting.

Table 5: Willingness to pay (WTP) for environmental quality (based on Ahlroth & Finnveden, 2011; Matos et al., 2010; Pizzol et al., 2015; ISO 14008)

Type of WTP	Valuation	Example
Observed WTP	Direct use value: market prices	Market price of natural resources
Revealed WTP	Indirect valuation (price of related marketed goods)	Lakeside property price
Expressed WTP	Surveys (stated preference)	Price for a change in life quality
Imputed WTP	Replacement / repair costs	Wetland restoration cost
Political / Society's WTP	Cost to reach political targets	Taxes

Monetary valuation can be applied to overall sustainability questions by juxtaposing the added value of the AEC sector to damages and changes in capital in the sector (Pearce, 2006). It thereby enables stakeholders to quantify the effect of damages or, the price a society pays in relation to the benefits of a sector. Monetary valuation indicates the range of potential internalization of environmental cost. Previous studies (Chou & Yeh, 2015) have coupled this concept with benchmark values applying taxes only above a certain benchmark instead of fixed costs per unit of emissions. This promises to provide additional incentives to reach political targets.

The very advantage of monetary valuation, the familiarity of the resulting values, bears the danger that it might suggest that environmental deterioration can be compensated for in economic terms, i.e., it only communicates weak sustainability. However, if it is made clear that the costs representing LCA results are of a different nature than costs in (financial) LCC, it proves to be a suitable method for the building design process.

2.2 Life Cycle Costing (LCC)

2.2.1 The LCC Method

The basis for LCC is the consideration of the entire life cycle of a product system. In this sense, LCC is the parallel method to LCA for economic considerations. Similar methods include whole life costing (WLC), total-life costing, total cost of ownership or ultimate life cost (Kishk et al., 2003). Per DIN EN 16627, WLC differs from and extends LCC by considering benefits in addition to the expenses included in LCC.

LCC is an established method standardized in several norms for different contexts. For dependability management, DIN EN 60300 defines life cycle cost as the „cumulative cost of a product over its life cycle". Possible purposes of LCC or LCCA (life cycle cost analysis) are, first, the use as a decision-making tool, e.g., in product development, and, second, as a management tool, e.g., as an instrument of asset management. LCC distinguishes between investment cost, cost of ownership and disposal cost (DIN EN 60300). Of these, first cost (initial cost) occurs in the present, whereas future costs recur either regularly or only at certain points in time throughout a product's life cycle. End-of-life cost at the end of a product's service life can consider salvage or residual value.

The calculation of future costs needs to take into account that the value of money changes over time. Discounting and price change rates are common factors used in this context. Generally, the discount rate depends on the investment horizon and individual preferences. It can be determined in the following ways:

- Interest rates, or the price at which money for an investment can be borrowed. Here, it is important to note the different stakeholder perspectives: Private and public discount rates may vary.
- Money that can be made in the interim: This depends on the investor and how an investor values the risks involved in an investment.
- Pure time preference („impatience"): An individual's preference of present over future cost and benefits or vice versa.

Therefore, discount rates are not a set value but must be determined on a case-by-case basis. The choice of a particular discount rate decisively influences LCC, especially if expenses at a later date are expected. If two investment possibilities are compared, one with higher initial cost, but lower follow-up cost (option 1) and another with low investment cost but high follow-up cost (option 2), the discount rate can tip the scale: a low discount rate will favour option 1, whereas option 2 is at an advantage if a high discount rate is chosen.

Historical data serves as a source for price change rates. These are typically distinguished between sectors of the economy or types of products to account for differing market situations (e.g., energy prices develop differently from construction prices). Price change rates influence LCC as strongly as discount rates but in the opposite direction. If high price increases are expected, amortisation times for investments aiming at saving recurring expenses are shorter. A common example is an investment for energy-saving measures: If energy prices rise sharply, the payback time for the investment is short.

Both discount rates and price changes are subject to uncertainty. It is important to understand how they influence future costs or benefits, and that they work against each other: High price changes cancel out high discount rates and vice versa. Additionally, their exponential effect is not to be underestimated, especially if an LCC study is concerned with a long study period.

2.2.2 Building LCC

The adaptation of LCC to buildings faces similar challenges as LCA does (section 2.1.2), namely the long life span of buildings, their unique nature and their complexity (Cole & Sterner, 2000).

LCC calculations receive increasing attention in the AEC sector as sustainability considerations shift the focus to future life cycle phases. However, implementation of LCC over initial cost calculations is not yet widespread despite its use for more than 30 years (Woodward, 1997). Kishk et al. (2003) identify three types of barriers: industry barriers, client barriers and analysis difficulties. A short investment horizon of developers leads to the exclusive consideration of initial investment cost. Clients might not consider maintenance or operation cost occurring after building hand-over, especially when they do not occupy the building themselves. The investment cost is perceived as a real cost and can be determined with relative certainty, whereas future costs are subject to higher uncertainties and do not have to be paid for immediately (Flanagan et al., 1987). Thirdly, data acquisition is a complicated and lengthy process.

ISO 15686-5 treats LCC in the context of service life planning. In parallel to building LCA standardization (DIN EN 15643-2), DIN EN 15643-4 contains the basic rules for building LCC. In LCC, like in LCA, a functional unit needs to be specified to ensure comparability of design alternatives. In contrast to LCA, normalization or weighting of different indicators are not required, as these are implied via market mechanisms. Although the standard mentions several levels of analysis for different life cycle stages (ISO 15686-5, 4.4.2), the structure for LCC studies is not as clearly outlined as the structure for LCA.

In more detail, DIN EN 16627 specifies the calculation method for the economic quality of buildings as a part of sustainability assessments. This is the “parallel” norm to DIN EN 15978. It specifies the LCC process to be comprised of eight elements (Figure 5).

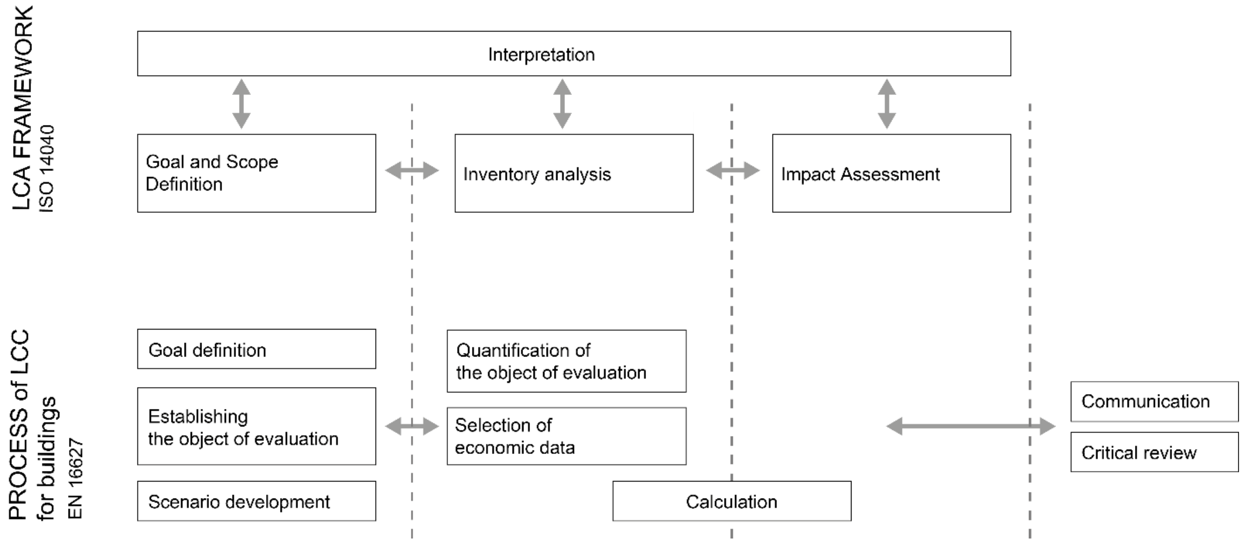

Figure 5: LCA framework per DIN EN 14040 and process of LCC per DIN EN 16627 (published in (Schneider-Marin et al., 2022a))

Different cost types apply depending on the life cycle phases (Figure 6), namely construction costs, maintenance and operation costs, and end-of-life costs. For construction costs, DIN 276 provides further information and a cost breakdown into cost groups (CG). For maintenance and operation, DIN 18960 applies, structuring the costs of building use in cost groups, too. Confusingly, both norms use the same numbering for cost groups, e.g., CG 300 per DIN 276 are the costs for the building’s structure and finishes, whereas CG 300 per DIN 18960 contains the costs for building operation (energy and water supply, waste disposal, cleaning, etc.). The CGs according to DIN 276:2018-12 were used in (Schneider-Marin & Lang, 2022) to decompose the building into its parts, elements and materials.

Similar to LCA standards, LCC standards do not specify the exact framework for analyses, such as functional units, study period or system boundaries. There is one exception to this observation: DIN EN 16627 incorporates a mandatory discount rate of 3% for building assessments while allowing for comparison with other discount rates if these are justified by client requirements, referencing the Energy Performance of Buildings Directive (EPBD) (EU regulation 244/12, 2012).

Similar to LCA results, the costs of building operation dominate the total life cycle costs of buildings. Several studies observed that for a commercial building user the cost of wages can exceed by far the cost of all other costs associated with a building, accounting for more than 90% of total life cycle costs (Cole & Sterner, 2000). This leads to the observation that measures increasing user satisfaction, comfort and productivity might have large secondary effects beyond measurable life cycle cost savings. Additionally, cost of labour is a decisive factor in building LCC even if it excludes wages not directly connected with building operation, because labour costs account for a large share in construction costs (Hillebrandt, 2000) and manual labour is needed in processes during building use (cleaning, maintenance).

2.2.3 LCC and Sustainability

In sustainability evaluation, LCC stands for the economic aspect. It serves to show that in some cases higher initial cost incurs lower total cost under a life cycle perspective, as it takes future expenses into account. Although the solution with the lowest life cycle cost might also be the solution with the lowest environmental impact, this is not necessarily the case (Steen, 2005).

LCC adopts a more holistic perspective than standard (investment) cost calculations. In doing so, it often crosses stakeholder boundaries when various actors own or use a product system in different life cycle phases. An investor with a short-term investment perspective might consider a solution which is favourable in the long term only if there is a possibility to communicate this quality to a potential buyer and thereby achieve a higher selling price. A recent example for the communication of use quality in consumer products are energy certificates, indicating that an investment in a more expensive, but more efficient product saves expenses in the long term.

2.3 LCA and LCC

Both LCA and LCC are well-established methods to analyse impacts throughout the life cycle of products and processes. Their integrated or parallel use is of strong interest in the context of sustainability striving for the triple bottom line of environmental, economic, and social quality. As this topic has received increasing research attention in the last decade, the state of current research was analysed and published in (Schneider-Marin et al., 2022a). A summary of the publication can be found in section 4.2.2. The following sections 2.3.1 to 2.3.3 provide additional background to the published results.

2.3.1 Methods

Most research integrating LCA and LCC uses both methods independently, but there is also a body of work using either one as the leading method at different degrees of integration (Meynerts et al., 2016). With LCA as the basic method, economic impacts become part of the environmental analysis to arrive at LCA-based costing (Meynerts et al., 2016; Miah et al., 2017), whereas environmental LCC considers external costs likely to be internalized or already internalized in LCC, sometimes juxtaposing environmental impacts and total costs (Hunkeler et al., 2008; Swarr et al., 2011). Introducing LCA into LCC by accounting for environmental impacts in LCC enables companies, amongst other benefits, to assess the financial risks of environmental pollution, if taxes or fees internalize external effects in the future (Steen, 2005). Monetary valuation of environmental impacts plays a role in all integrated methods as a way to consider environmental effects in an economic context.

Next to process-based LCA and LCC, other methods exist to calculate life cycle impacts. As top-down (input-output) LCA is connected to economic considerations because it allocates emissions by economic activity (see 2.1.1), it seems to be an obvious choice for LCA-LCC integration. However, the AEC sector is an “activity” rather than a sector, as it touches on different sectors of the economy (Habert et al., 2020), making input-output analysis much less straightforward. As a consequence, none of the 30 case studies analysed in (Schneider-Marin et al., 2022a) used input-output LCA.

Material Flow Cost Accounting (MFCA) was originally developed as a management tool, to track material flows within a production company, identifying material losses or inefficient use of materials (Wagner, 2015). This analysis can be extended to reflect both environmental and economic impacts of the material flows, enabling a parallel analysis, as it employs a common LCI (Bierer et al., 2015). As a method, it is currently not usable in building evaluation, because it requires large, disaggregated datasets for materials and processes in buildings. Such datasets are not available. Additionally, MFCA would add another level of complexity to building LCA and LCC already preventing a widespread use. However, the underlying idea of aligning background data increases the efficiency of a parallel LCA and LCC and should be kept in mind for future developments.

2.3.2 Common Ground

Both methods have undergone standardization (Figure 5), but there is no standard for using LCA and LCC in parallel However, they share a number of common definitions and methods. A brief overview is given in the following sections, more detailed information is published in (Schneider-Marin et al., 2022a).

2.3.2.1 The Building Life Cycle

Both methods subdivide the life cycle in several phases, also named “stages” or “modules” (Figure 6). For cost considerations, the life cycle begins with phase 0, containing all expenses or “immaterial costs” related to project preparation and site acquisition (DIN EN 15643-4 and DIN EN 16627). This phase is unique to the LCC method, i.e., LCA currently does not consider it. The names of all other phases thereafter are very similar or identical for LCA and LCC.

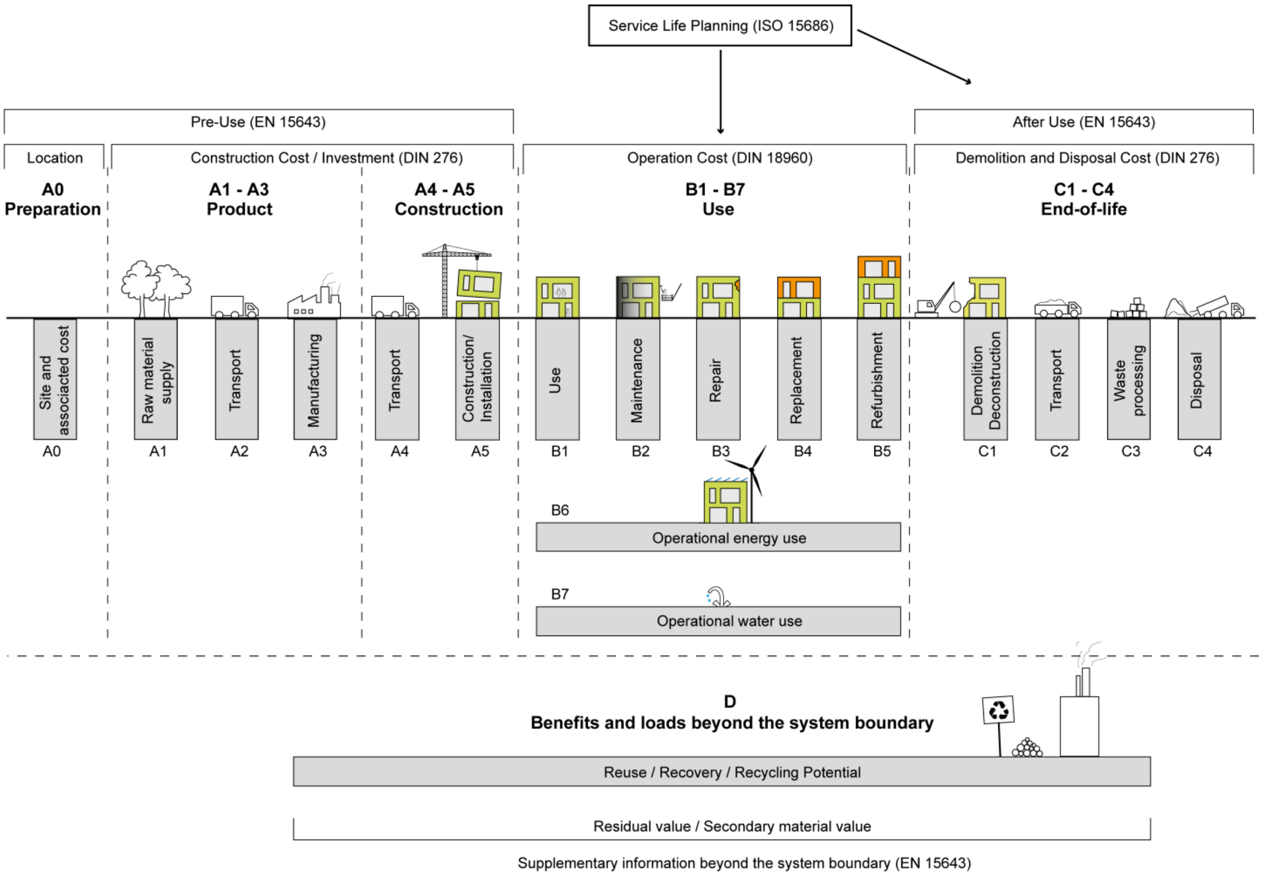

Figure 6: Life Cycle phases (stages, modules) according to DIN EN 15643-2, DIN EN 15978, DIN EN 15804, DIN EN 16627 and related standards[2] (A similar representation is published in (Schneider-Marin et al., 2022a).)

The product (A1-A3) and construction (A4-A5) phases follow with their respective sub-phases. When the building is handed over to the client, the use phase (B) begins, the longest phase in a building's life cycle. This phase is divided again into sub-phases, with irregularly (B1-B5) and regularly (B6, B7) recurring expenses and impacts. At the end of a building's life cycle, phase C with de-construction and waste treatment or disposal occurs. After phase C, the materials contained in the building leave the building's system boundary. However, there is one more phase (D) after the building life cycle, serving to quantify benefits and loads outside of the system boundary.

Although the majority of recent studies attempts to consider the whole life cycle (Saade et al., 2020), standard life cycle calculations exclude some life cycle phases for different reasons. For Environmental Product Declarations (EPD), phases C and D became mandatory as late as in the year 2020 (DIN EN 15804:2020-03). Before that, it was sufficient to include phases A1-A3 in the LCA (DIN

[2] The naming in the German versions of the norms differs slightly between norms. Numbering and definitions of boundaries are consistent.

EN 15804:2014-07). The German evaluation systems DGNB and BNB for building sustainability include A1-A3, B4, B6 and C3-C4 in LCA calculations. The DGNB system allows for the inclusion of phase D (DGNB GmbH, 2018b), whereas the BNB system does not (BMUB, 2015b).

Standard-LCA often disregards site-related processes (A4, A5, C1, C3). These processes are typically project-specific and hence more difficult to evaluate than standard production processes of building products. Moreover, earlier studies determine the impact of these phases to be negligible (Bahramian & Yetilmezsoy, 2020; Sartori & Hestnes, 2007). More recently, however, construction processes have gained attention (Takano et al., 2014), as the importance of the material and construction phase increases with diminishing non-renewable energy consumption and related emissions in the use phase (B6) (see also section 2.1.2).

The use phase dominates the long life cycles of buildings, both in terms of its length and because of its energy use and environmental impacts. In this phase, buildings require conditioning to provide a comfortable environment (B6), maintenance (B2), cleaning (B2) and repair (B3). Operational energy use in older buildings largely determines life cycle energy use and cost. However, a difference between LCA and LCC results appears to be that the share of life cycle phase B6 in total environmental impacts is consistently larger than its share in economic impacts (BMUB, 2015c; Schneider-Marin et al., 2019). Even in nearly zero energy buildings, a 50 year long use phase can still be responsible for 35% of environmental impacts while it causes only 20% of life cycle costs (Sanchez et al., 2017).

Materials that reach the end of their life cycles are exchanged (B4) and some buildings are refurbished (B5). There are multiple uncertainties related to these processes. As the end-of-life phases of these materials and of the entire building lie in the far future, uncertainties about available recycling technologies are high. Additionally, the length of the service life of the building and potential building refurbishment might depend on factors outside of the system boundary, e.g., economic conditions or a particular urban surrounding.

Both, LCA and LCC, currently lack data on end-of-life impacts (phase C and D), as there are almost no alternative scenarios available. Furthermore, there is rarely any end-of-life data available at all for LCC. The end-of-life phases face the highest uncertainties, as they lie far in the future, i.e., available processes and technologies are unknown.

Not every life cycle phase is as relevant for LCA as it is for LCC, because the underlying drivers differ. As a rule of thumb, labour-intensive life cycle phases (e.g., A5, B2, C1) are decisive for LCC results, while material intensive (A1-A3, B4) and energy consuming (B6) life cycle phases tend to determine LCA results. One reason for this is the fact that labour costs in the AEC sector contribute a large share of the cost, while labour is not accounted for in LCA calculations as it is outside of the system boundary. This is justified because manual work does not cause a large amount of emissions. Including secondary emissions from employees' travel, consumption etc. would eventually result in a system boundary, which is too wide to be meaningful for a design process. It would provide input for project development, e.g., the choice of one construction site over another or the choice of construction companies for the execution of the project.

2.3.2.2 System Boundaries and Functional Units

The definition of spatial and temporal system boundaries and functional units is a mandatory part of both the LCA and LCC method. The functional unit is an important parameter in life cycle studies, as comparisons of different product systems are based on the assumption that both systems fulfil an equivalent function. Therefore, the functional unit must be chosen with care and in line with the goal and scope of the study. Typical functional units for buildings are geometry based, e.g., useable floor area, heated floor area or volume. Interestingly, the BNB and DGNB certification systems specify net floor area (NFA) for LCA, but gross floor area (GFA) for LCC (BMUB, 2015a, 2015b; DGNB GmbH, 2018a, 2018b). When comparing buildings of different geometries, the use of one functional unit versus another can strongly influence results. Buildings with a high floor-to-floor height would be at an advantage with volume as part of the functional unit whereas buildings with low ceilings would appear better based on floor area. More recently, user-centred functional units (e.g., personal CO_2-footprint) gain importance (Hoxha et al., 2020a). This addresses the problem that the increasing per capita floor area in developed countries counteracts efficiency measures.

2.3.2.3 Temporal Parameters

A decisive temporal parameter in a building life cycle study is the length of the study period. Long study periods put emphasis on the use phase, whereas in shorter study periods the focus shifts to the phases at the beginning and the end of a building's life cycle. The choice of the study period should reflect the goal and scope of the study as well as influential characteristics of the building such as function or construction quality. In most recent building LCAs, the study period is defined to be 50 years (Cabeza et al., 2014; Moncaster et al., 2019; Saade et al., 2020; Sharma et al., 2011) but for some building types and for sensitivity analyses, 30 up to 100 years are considered (Bahramian & Yetilmezsoy, 2020).

Building parts and materials with a reference service life (RSL) shorter than the study period need to be exchanged during the study period. As a basis for the number of exchange cycles, standard building LCA considers the technical life span, disregarding other factors such as tenant changes. This information is attached to the material data and the location of the material in the building. As the actual service life is subject to high uncertainties, (Goulouti et al., 2020; Goulouti et al., 2021) recommend using probabilistic service life distributions. The length of service lives influences the overall amount of material used in a building. Hence, longer service lives can save emissions and cost at the same time, if they do not involve more expensive, but more durable materials, but strategies to prevent premature material failure. In parallel LCA and LCC studies care must be taken, that RSLs are aligned, i.e., a building part is changed at the same time in economic and environmental accounting instead of using functional RSL for environmental and economic RSL for economic calculations. These can substantially differ, as the end of functional service life is reached at technical failure, whereas the end of the economic service life is reached when replacing an element costs less than keeping it in place (Hartman & Tan, 2014).

The set of temporal parameters without a direct relation to the building are discount and price change rates (see section 2.2.1). Standard LCA does not apply these parameters. Moreover, discounting emissions is questionable from an ethical point of view as it suggests intergenerational inequality. On the other hand, if emissions are converted to currency values these figures should be subject to similar calculations as financial cost (Hellweg et al., 2003).

2.3.3 LCA and LCC in the Building Design Process

Only investment cost calculations are stipulated by the German fee structure for architects and engineers (Deutsche Bundesregierung, 2013) as part of a standard building design process. Introducing the life cycle perspective and the environmental perspective bears the opportunity to identify improvement opportunities early in the process when they can be implemented at low cost and effort (Figure 1).

2.3.3.1 Early Design

There is no generally accepted definition of early design phases, as the professional bodies in various countries define the design process in different ways. For a brief overview, see for example (Schneider-Marin & Abualdenien, 2019). However, the early phases of special interest for decision-making are the phases in which decisions can still be reversed at low expense of time and money. Within the design process, these early phases largely determine both life cycle costs as well as environmental impacts (Bogenstätter, 2000). Therefore, they contain the best opportunities to reduce impacts and increase efficiency. At the same time, in early design phases, information regarding the future building is subject to high uncertainties or lacking altogether. Extensive variant studies requiring estimates and assumptions in many areas (dimensions, materials, processes, etc.) are too time-consuming for a regular design process.

Adjusting the granularity of LCA and LCC calculations to the level of detail of the design offers a possible remedy. Cost calculation for buildings per DIN 276 uses this strategy, starting with cost estimation based on general building characteristics (e.g., building use, standard, GFA, etc.). The costs are calculated with increasing detail as the design progresses. However, currently this only applies to construction costs (i.e., life cycle phases A1 to A5), and it requires data at different levels of granularity with functional units adjusted to the design phase. A transfer of this method to LCA requires corresponding environmental data. To achieve this, a number of as-built projects need to serve as data sources for total impacts as well as to identify the building qualities with the largest influence on environmental impacts. To date, such data is not available, as LCA, unlike cost calculation, is not a standard task in building design.

In early design stages, high design uncertainty aggravates uncertainties pertaining to LCA and LCC parameters. In order to be able to provide a complete analysis, analysts estimate future buildings properties in collaboration with architects and engineers, e.g., thermal properties of the building skin or window-to-wall ratio. The BIM-based sensitivity analysis in publication 4 (Schneider-Marin et al., 2020) identifies parameters causing high result uncertainties and analyses the contribution of building sub-systems. This analysis provides design guidance for the reduction of greenhouse gas emissions. Including LCA and LCC parameters as outlined in the previous section should extend and further specify this method in the future. Additionally, the knowledge database in publication 5 (Schneider-Marin et al., 2022b) lays the groundwork for enriching environmental data with additional information and categorizing materials and products to make them more accessible in building design.

Efforts to include LCA and LCC separately in early design stages have been developed, including simplified (Lasvaux, 2010) or streamlined (Hester et al., 2018) LCA, which focuses on the most influential inputs and the (perceived) main impacts. For LCC, early design BIM-based cost estimation (Lee et al., 2020; Santos et al., 2020) has been conducted. For building retrofits, (Rodrigues et al., 2018) developed a BIM-based streamlined approach. The authors identify environmentally and economically favourable retrofit options using under-specification (Olivetti et al., 2013), i.e., data at different levels of granularity, and probabilistic triage, choosing the most influential data-subsets for more detailed specification. In general, digital tools are sought to avoid data collection efforts and facilitate variant generation in design. In the context of the EarlyBIM project (Abualdenien et al., 2020), the methods developed in this study will be the basis for digital implementation.

2.3.3.2 Integration and Representation of Results

In environmental-economic calculations, the problem arises how to weigh results against each other and how to communicate options to stakeholders. Publication 2 (Schneider-Marin et al., 2022a) provides a comprehensive overview of the methods used in previous studies, concluding that the most prevalent method is the juxtaposition of costs and one representative or aggregated environmental indicator. Only very few studies include monetary valuation and add environmental costs to financial costs to arrive at an unequivocal basis for decisions.

Certification systems weigh each sustainability criterion to reach an overall conclusion about a building’s sustainability rating. Meanwhile, they do not indicate which criteria might counteract each other or which might provide opportunities for synergies. In the BNB and DGNB system, both LCA and LCC criteria are included in the calculation (Table 4). Over time, a consensus appears to have emerged that LCA and LCC should have roughly equal weights, with the exception for small residential buildings (BNK system), in which the economic criterion outweighs LCA by a factor of 3,5.

Despite the high number of possible graphic representation of LCA results (Hollberg et al., 2021), result representation methods for environmental-economic evaluation have been limited to bar charts and vector representation (Schneider-Marin et al., 2022a).

3 Eco² Approach and Methodology

Beyond the synergies and challenges described in section 2.3, a parallel LCA and LCC evaluation with weighting of environmental impacts by monetary valuation has the following advantages (see also (Schneider-Marin et al., 2022a)):

- Comprehensive overview of environmental and economic impacts enables decision making on a sound basis.
- Streamlined data acquisition for inventory data avoids errors and unnecessary duplication of efforts.
- LCA and LCC methods mutually enrich each other.
- Monetary valuation of environmental impacts allows visualization of both internal and external effects in the same unit.

However, multiple challenges arise in the process. As a remedy for the lack of specifications and data for both methods, building sustainability certification systems (BMUB, 2015b, 2015c; DGNB GmbH, 2018a, 2018b)) provide valuable sources of information, such as cost for recurring cleaning and maintenance. A transfer of methodological choices from LCA and LCC and vice versa allow to align LCA and LCC. This process identifies necessary input parameters and generates an applicable framework.

Data is not available for both LCA and LCC in parallel. Therefore, data acquisition is complex and lengthy, often requiring the use of multiple sources and different granularity of the data, e.g., emissions on a building product level, but costs for entire building parts. The project-specific data collection developed in (Schneider-Marin & Lang, 2022) is intended to serve as the basis for further data generation (section 3.1.2). For ecological data, the knowledge database developed in (Schneider-Marin et al., 2022b) restructures and enhances Ökobaudat data for use in early design processes. Cost data can be introduced into this database to make it usable for harmonized LCA and LCC calculations.

Monetary valuation is not a standard process in building LCA in Germany, hence the first step is to test the practicability and validity in the context of Ökobaudat. Different valuation methods from literature provide base values for the conversion of emissions to environmental costs. A set of six sample projects serves to illustrate the impact of varying costs for different types of emissions (Schneider-Marin et al., 2020). In addition, statistical methods showed that these observations are consistent with the available underlying LCA data for buildings within the database Ökobaudat (Bundesministerium des Innern, für Bau und Heimat [BMI], 2020) (Schneider-Marin & Lang, 2022). We conclude that monetary valuation provides consistent weighting of impacts, but the magnitude of environmental costs differs greatly. Only valuation of building related emissions on the high end of values found in literature is representative for the perceived high contribution of the construction industry to environmental impacts.

3.1 Integration of Building LCA and LCC

Although LCA and LCC already share several common steps and requirements (Figure 5), they lack a clear framework definition for an integration of the two methods. Therefore, such a framework was developed in (Schneider-Marin et al., 2022a), and applied to a case study in (Schneider-Marin & Lang, 2022).

3.1.1 Goal and Scope Definition

The goal and scope definition needs to specify the same study period, equivalent system boundaries and the same functional unit. For the case studies in (Schneider-Marin et al., 2020; Schneider-Marin & Lang, 2020, 2022), certification systems provide the study period of 50 years. For the spatial system boundaries, LCA is still decisive as data gaps are currently higher in environmental than economic data. As such, the LCC contains all building parts and services which LCA can include in the analysis. This accepts the possible downside of missing economic drivers whose effect on the environment is currently not quantifiable, because it has the advantage of identifying the main drivers for environmental and economic impacts in parallel. A harmonized analysis of when and where impacts occur requires the definition of a base year for all costs and (monetized) environmental impacts. For the case studies this is the year 2020 (Schneider-Marin & Lang, 2022) or 2015 (Schneider-Marin & Lang, 2020) respectively.

Standard LCA neglects life cycle phases A4 (transport) and A5 (construction/installation) due to the lack of data for these processes, as they are individual to each building project. In contrast, construction prices include transport and installation because they contribute a large share of the cost. For the case study (Schneider-Marin & Lang, 2022) this discrepancy is accepted to take into account the effect of materials that allow for more efficient installation processes and avoid excluding this important cost parameter. In parallel, LCC includes deconstruction and transport at the end of the building's service life, whereas LCA excludes these processes. For future analyses, data collection for the inclusion of these life cycle phases is necessary.

Use (B1) and refurbishment (B5) are not included in the analysis, the former due to a lack of data. Complete refurbishment (B5) requires a scenario analysis depending on the function and design of the building and its surrounding conditions. As these factors depend only marginally on the material composition of the building, life cycle phase B5 is out of the scope of this analysis.

Life cycle phase B3 (repair) is often excluded from LCA. LCC on the contrary includes repair requirements by adding a percentage of the initial cost (life cycle phase A1-A5) per year. Different percentages apply to different building parts. As an approximation of life cycle impacts, the same percentages (of A1-A3 impacts) were applied in the LCA calculation to account for the lack of data.

The framework includes a scenario analysis, as building design processes require an iterative process and a robust basis for decision making. In (Schneider-Marin & Lang, 2022), the scenario analysis includes a variation of the building's subsystems, energy generation, temporal parameters and monetary valuation.

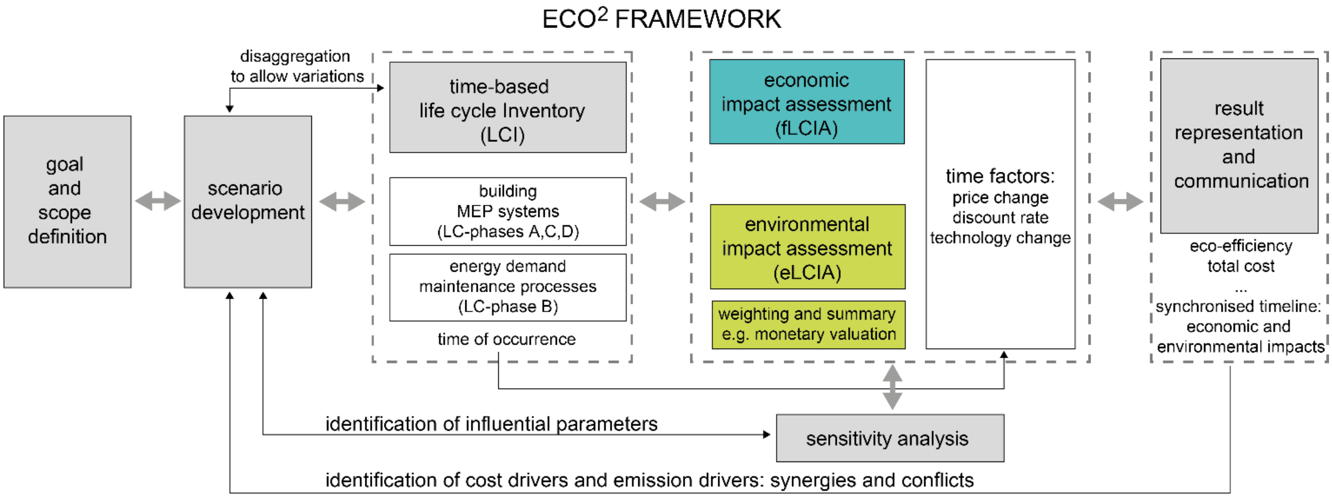

Figure 7: The Eco² framework (Schneider-Marin et al., 2022a)

3.1.2 Life Cycle Inventory

The time-based life cycle inventory contains all data necessary for the analysis. DIN 276:2018-12 provides the breakdown of the building into its subsystems (cost groups CG), structure and finishes (CG 300) and MEP systems (CG 400) (Table 6).

Table 6: Selected cost groups (CG) per DIN 276:2018-12 (translated by the author) for disaggregation of the building into elements, building parts and building systems.

CG building system	CG building parts	CG building elements
300 Building – structure and finishes	320 Foundation	322 Base Plate 324 Flooring on base plate 325 Layers under base plate
	330 Exterior walls – Vertical exterior building parts	331 Ext. load-bearing wall 332 Ext. non load-bearing wall 334 Ext. openings 335 Ext. finish and insulation 336 Interior cladding on ext. walls
	340 Interior walls – Vertical interior building parts	341 Int. load-bearing wall 342 Int. non load-bearing wall 344 Int. openings 345 Cladding on int. walls
	350 Floors / ceilings – horizontal building parts	351 floor slab 353 flooring 354 cladding (underside)
	360 Roofs	361 roof construction 363 roofing 364 cladding (underside)
400 MEP system	410 Sewage, Fresh water, gas systems	
	420 Heat supply systems	
	430 Ventilation systems	
	440 Electrical systems	

Recombining different sub-levels for each system allows for a best case (and worst case) solution, based on knowledge which subsystems are compatible.

To provide consistent data for LCA and LCC calculations and a proof of concept for the methodology, a limited dataset for both based on the sample project FTMehrHaus (Vollmer et al., 2019) was created. The particular challenge of this exercise was the appropriate aggregation or disaggregation of data to align with material exchange cycles, and to enable variation of construction materials and MEP systems (Schneider-Marin & Lang, 2022).

3.1.3 Temporal Parameters

Standard net present cost calculation serves to add a temporal perspective to LCC. A sensitivity analysis with varying discount and price increase rates determines the influence of these parameters on decisions. This idea transferred to LCA introduces a time aspect via the valuation of future emissions. (Schneider-Marin & Lang, 2022) discusses the effects of varying temporal parameters on the comparison of different solutions for the same building.

3.1.4 Representation of Results

For the representation of results, a vector representation and a timeline allow for detailed interpretation and for tracking of impacts to different times in the life cycle of the building and to the building sub-systems. Vector representation shows the relationship between financial life cycle cost (fLCC) and environmental life cycle cost (eLCC) revealing solutions incurring high or low environmental impacts per monetary unit spent. Timelines represent the results of LCA and LCC in parallel, separated in structural and finish materials (CG3 300) and mechanical systems (CG 400) in conjunction with the operational phase (B6) of the building. As such, hotspots in the lifetime of the building can be identified, as well as mutual influences between energy generation and operational impacts.

3.2 Environmental Costs

For the Eco^2 approach, environmental cost (EC) values serve two purposes. First, monetary values determine the weighting and enable aggregation of the different environmental impact categories. Second, juxtaposition of the resulting aggregated LCA value with LCC results is possible, using the same monetary unit.

The several different valuation models (see section 2.1.4.4) provide strongly differing values for the mid-point impacts of interest for the application in building life cycle assessment (Arendt et al., 2020). After investigating the effect of the change in valuation in (Schneider-Marin & Lang, 2020), the harmonized impact assessment (Schneider-Marin & Lang, 2022) varies the influential values (GWP, AP, ADPE) at the high end of the spectrum to take into account the perceived high environmental impact of the AEC sector. At the same time, the resulting timelines show eLCC and fLCC juxtaposed without adding both cost types for three reasons. Firstly, uncertainty in monetary valuation is higher than for financial costs based on market prices. Secondly, despite both results using the same unit, the nature of the costs involved differs strongly. Financial costs are to be paid for by an individual or an organisation, e.g., the investor and/or the future owner of the building, whereas environmental cost is the cost society as a whole can expect from the impacts caused by the building and its use. Thirdly, different time factors, price change and discounting, apply to each cost type respectively. Keeping environmental cost separate from financial (market) costs allows for a detailed scenario building and sensitivity analysis.

3.3 Sample Projects

Sample projects provide the objects for the testing of all methods and assumptions. The main sample project is the FTMehrHaus of Tausendpfund GmbH in Regensburg, Germany, built in 2016 (Vollmer et al., 2019). For this building, detailed execution plans and specifications were made available by Tausendpfund GmbH, enabling a complete as-built LCA and LCC. An extensive variant study was conducted based on architectural experience to test the robustness of the developed methods.

The research project Design2Eco (Schneider-Marin et al., 2019) provided an additional five sample projects which served for the initial investigation into monetary valuation of environmental impacts and their relationship to the life cycle costs.

4 Results

Results obtained from this study are published in five articles summarized in the following sections 4.1 through 4.5. Publications 4.1, 4.2 and 4.3 are the core publications related to environmental-economic assessment in building design. The two related publications 4.4 and 4.5 tackle aspects of early design LCA which are at the basis for the environmental aspects in the core publications.

The related publication on early design LCA (section 4.4) analyses a representative part of CG 300 using a BIM-based LCA. The environmental indicators considered are energy-related (PERT, PENRT) and GWP. In cooperation, colleagues Hannes Harter and Manav Mahan Singh conducted a conjoint analysis with the operational energy use (phase B6) (Harter et al., 2019).

As the available data for environmental impacts does not lend itself to early design applications, a knowledge database restructuring LCA data was developed by enriching it with information a designer would search for in early design phases, such as general material categories and applicability of a material within a building (section 4.5). This provides insight on data availability and required information structure to use environmental data in building design.

The core publications progress in the level of detail of the investigation and the extent of their system boundaries (Figure 2). The initial investigation summarized in 4.1 tests the validity of using monetary valuation for weighting in building LCA. It includes a set of five mid-point environmental indicators and resource consumption for the building's structure and finishes (CG 300) and juxtaposes them with a standard LCC of the buildings. The second core publication (section 4.2) contains a literature analysis about LCA and LCC integration, focussing on the AEC sector. This informs the development of a framework for integrated LCA and LCC in building design. Finally, the publication integrating LCA and LCC (section 4.3) applies the framework and completes the spatial system boundary by not only considering CG 300 and variations, but also CG 400 and operational energy use. Moreover, it adds the temporal dimension to monetized environmental impacts to fully integrate both methods and provide a wider perspective on building evaluation.

4.1 Environmental Costs of Buildings: Monetary Valuation of Ecological Indicators for the Building Industry (Publication 1)

Schneider-Marin, Patricia; Lang, Werner (2020): Environmental costs of buildings: monetary valuation of ecological indicators for the building industry. International Journal of Life Cycle Assessment 25 (9), pp. 1637–1659. DOI: 10.1007/s11367-020-01784-y.

4.1.1 CRedit author statement

Patricia Schneider-Marin: Conceptualization, methodology, investigation, calculations, visualization, writing - original draft preparation, funding acquisition
Werner Lang: Supervision, writing - review and editing, funding acquisition

4.1.2 Summary

This publication applies monetary valuation to the LCA results of a set of office buildings to evaluate the applicability of monetary valuation as a weighting and communication method in building design. The work seeks to answer research question 2 (section 1.2), if monetary valuation provides consistent weighting and thereby indicates the environmental impacts with the highest contribution to environmental cost. It contributes to research question 3 (section 1.2) by juxtaposing environmental impacts to the results of economic assessment. This shows the influence of a potential internalization of external environmental cost.

A set of five recent German office buildings from a previous research project (Schneider-Marin et al., 2019) and an additional office building in fifteen variations served as a case study. LCA and life cycle cost (LCC) calculations for these buildings followed the framework of German certification systems, e.g., a study period of 50 years, discount and price change rates in LCC according to the BNB system (BMUB, 2015c) and static LCA with Ökobaudat as underlying data. The calculations included the embedded impacts for the buildings' structures and finishes, but not for the mechanical, electrical, and plumbing (MEP) systems.

Monetary valuation models from the literature were gathered and compared as a basis for conversion of environmental impacts to environmental cost (EC). "From these, maximum and minimum valuation was chosen and applied to the LCA results for the embedded impacts of the case study buildings. The buildings' EC were thereafter calculated, and contributions of single impacts are analysed." (Schneider-Marin & Lang, 2020) The choice of impact categories followed the selection stipulated in DIN EN 15804:2014-07 and the currently available data, taking into account the following five impact categories: global warming potential (GWP), acidification potential (AP) eutrophication potential (EP), photochemical oxidization potential (POCP), and ozone depletion potential (ODP). Of these, "GWP contributes approximately 80 to 95% of the overall EC. Acidification potential (AP) is the second largest contributor with up to 18%. Eutrophication (EP), photochemical oxidization (POCP), and ozone depletion potential (ODP) contribute less than 2.0%, 1.05%, and 2.4E−6% respectively. An additional assessment of the contribution of resource depletion to EC shows an impact at least as large as the impact of GWP. Moreover, the variation of construction materials for one of the case study buildings shows that materials with low GWP have the potential to lower environmental costs significantly without a trade-off in favour of other indicators." (Schneider-Marin & Lang, 2020)

The EC from this calculation were subsequently compared with the LCC of the respective buildings, at minimum and maximum valuation. This showed that the relation between the EC and LCC strongly depends on the EC model used: If EC were internalized at minimum valuation, they add only roughly 1% to the life cycle cost of buildings. At this valuation, it is doubtful that an internalization of EC would provide leverage towards more environmentally friendly solutions. On the other hand, at maximum valuation, EC amount to up to 37% of the life cycle costs of the buildings, a potentially meaningful influence if total cost were considered in decision making.

"Despite their sensitivity to the monetary valuation model used, EC provide an indication that GWP and resource depletion—followed by AP—are the most relevant of the environmental indicators currently considered for the construction industry. Monetary valuation of environmental impacts is a valuable tool for comparisons of different buildings and design options and provides an effective and valuable way of communicating LCA results to stakeholders." (Schneider-Marin & Lang, 2020)

The study focussed on the environmental impacts and their weighting by monetary valuation, using economic impacts as a backdrop to put the resulting EC into perspective. However, it revealed that LCC calculations are not entirely aligned with LCA calculations, neither in the life cycle phases included nor in the consideration of future impacts. Therefore, the following publication 4.2 seeks to analyse previous research on LCA and LCC integration and develop a method to align environmental and economic life cycle perspectives.

4.2 Integrating Environmental and Economic Perspectives in Building Design (Publication 2)

Schneider-Marin, Patricia; Winkelkotte, Anne; Lang, Werner (2022): Integrating Environmental and Economic Perspectives in Building Design. Sustainability 14 (8), 4637. DOI: 10.3390/su14084637.

4.2.1 CRedit Author Statement

Patricia Schneider-Marin: Conceptualization, methodology, formal analysis and investigation, data curation, writing - original draft preparation, visualization
Anne Winkelkotte: Writing - review and editing
Werner Lang: Writing – review and editing, Supervision, funding acquisition

4.2.2 Summary

The second publication contains, firstly, a literature review on life cycle assessment (LCA) and life cycle costing (LCC), focusing on the architecture, engineering and construction (AEC) sector. Secondly, a framework for an integrated application in building design is developed. It is partially based on the master's thesis of Anne Winkelkotte (Winkelkotte, 2019), who co-authored the publication.

The literature review showed that research on environmental-economic life cycle assessments has received increasing attention in the last decade, because LCA and LCC have great potential for answering a multitude of questions related to building performance. "Prevalent topics in the AEC sector are the implications of LCA and LCC for retrofit solutions and the trade-offs between environmental and economic considerations in building design." (Schneider-Marin et al., 2022a)

Thirty case studies were chosen for a detailed analysis of their calculations, including our own publication (summarized in section 4.1) in order to compare it to the body of previous research on the subject. The analysis of common metrics showed that the description of methodological framework is missing in most studies, as well as a clear definition of temporal and spatial system boundaries. LCA and LCC calculations were mostly employed independently, so that it was unclear if and how they are aligned. This prevents result comparison and the transfer of strategies of knowledge from one study to another. The investigation revealed a wide range of differing result integration methods. Monetary valuation for environmental indicators as a weighting method was found only in one other study. Most other studies seeking to summarize LCA results employed GWP as the representative indicator, some of which applied a price to greenhouse gas emissions.

Most studies used a quasi-dynamic approach in LCC calculations, accounting for the changing value of money over time by taking discounting and / or price changes into account. This approach is largely absent from LCA in this context. None of the studies discounts emissions, but one study applied a 1% discount rate to the monetary valuation of environmental impacts.

As a lack of framework was identified, the study developed an “Eco^2” framework, integrating LCA and LCC for application in building design (see also section 3). This framework outlines the steps for economic-environmental evaluation in building design and allows for a comparable description of the boundary conditions of future studies.

The following gaps were identified as subjects for further development and application of the Eco^2 building assessment to be filled in the following publication (section 4.3):

- collect and structure data
- extend the system boundaries by including mechanical systems and end-of-life phases
- employ temporal parameters in both LCA and LCC and investigate their influence on design decisions.

A future research opportunity is a detailed analysis, if and how the choice of particular result integration and communication methods influences design decisions. Additionally, streamlining the Eco^2 approach is necessary for continuous application to all stages of building design processes.

4.3 A Temporal Perspective in Eco^2 Building Design (Publication 3)

Schneider-Marin, Patricia; Lang, Werner (2022): A Temporal Perspective in Eco^2 Building Design. Sustainability 14 (10), 6025. DOI: 10.3390/su14106025.

4.3.1 CRedit Author Statement

Patricia Schneider-Marin: Conceptualization, methodology, formal analysis and investigation, data curation, writing - original draft preparation, visualization, funding acquisition
Werner Lang: Writing - review and editing, supervision, funding acquisition

4.3.2 Summary

This third publication applied the Eco^2 framework to a case study, addressing the research gaps described in 4.2. A project-specific data collection contains environmental and economic data for variations of the building sub-systems (CG 300 structure and finishes, CG 400 MEP systems) and for recurring impacts throughout the life cycle of the building. Monetary valuation and temporal factors were applied to LCA and varied in parallel to the temporal factors in LCC to analyze their influence on design decisions. Additionally, the scenario analysis allowed further insight into the relationship between environmental and financial cost.

In the standard scenario, the choice of a solution for CG 300 and CG 400 does not have a great influence in the financial LCC (fLCC), whereas the environmental LCC (eLCC) of the solutions differ strongly. This implies that eLCC, i.e., emissions, can be saved at a low fLCC premium, with some solutions providing the opportunity of simultaneous emissions (eLCC) and cost (fLCC) saving. The corresponding timelines reveal that eLCC of CG 300 stay below the fLCC throughout the building's lifetime, but the eLCC of MEP systems and building energy use in operation (CG 400 + B6) exceed the fLCC for most solutions. Keeping in mind that GWP is the highest contributor to eLCC, this was to be expected, because operational efficiency measures have been identified as the most cost-efficient GHG emissions savings strategies (Mc Kinsey & Company, 2009).

"Varying the temporal parameters affects the ranking of different solutions for the structure and finishes of the case study building, but not for its mechanical, electrical and plumbing systems (CG 400) and operation (B6)." (Schneider-Marin & Lang, 2022) In the standard and low time preference scenario (i.e., low discount and high price change rates), the influence of end-of-life emissions is extremely high and, consequently, the inclusion or exclusion of phase D impacts decisively influences the basis for decisions.

The ratio of environmental life cycle cost (eLCC) to financial life cycle cost (fLCC) strongly depends on the monetary valuation framework used, but also on the temporal parameters. If total cost, the sum of eLCC and fLCC, provides the basis for recommendations, including eLCC has the potential to leverage decisions towards the solutions with the lowest environmental cost, unless environmental impacts are valued at their minimum.

"This investigation shows that it is possible to achieve simultaneous emission and cost savings, while temporal factors and monetary valuation can decisively influence decision making in design processes." (Schneider-Marin & Lang, 2022)

4.4 Uncertainty Analysis of Embedded Energy and Greenhouse Gas Emissions Using BIM in Early Design (Publication 4)

Schneider-Marin, Patricia; Harter, Hannes; Tkachuk, Konstantin; Lang, Werner (2020): Uncertainty Analysis of Embedded Energy and Greenhouse Gas Emissions Using BIM in Early Design. Sustainability 12 (7), 2633. DOI: 10.3390/su12072633.

4.4.1 CRedit Author Statement

Patricia Schneider-Marin: Conceptualization, methodology, validation, writing - original draft preparation, visualization, funding acquisition
Hannes Harter: Methodology, software, writing - review and editing
Konstantin Tkachuk: Software, validation, writing - review and editing
Werner Lang: Writing - review and editing, funding acquisition

4.4.2 Summary

The uncertainty analysis for early design phase LCA uses a parameter-based sensitivity analysis and couples this with an analysis of the contribution of the structural system, the exterior walls and windows, and the interior walls, to embedded energy and GHG emissions. The study introduces a building information modelling (BIM)-based method to find embedded energy demand and GHG emission reduction potentials. “At the same time, a sensitivity analysis shows the variance in results due to the uncertainties inherent in early design to avoid misleadingly precise results. The sensitivity analysis provides guidance to the design team as to where to strategically reduce uncertainties in order to increase precision of the overall results.” (Schneider-Marin et al., 2020)

A case study based on the Tausendpfund building (Vollmer et al., 2019) shows that the variability and sensitivity of the results differ between environmental indicators GWP, PENRT and PERT, and construction types (wood or concrete). The sensitivity analysis progresses in line with the building development level (BDL), strategically reducing the uncertainty in input parameters to reduce overall uncertainty. Variability can be reduced systematically by first reducing vagueness in geometrical and technical specifications and subsequently in the amount of interior walls. For this case study, it is impossible to reduce all result uncertainties simultaneously, as result uncertainties for the various indicators (GWP, PENRT, PERT) depend on different input parameter groups (e.g., amount of interior walls, window-to-wall ratio).

“The case study contribution analysis reveals that the building’s structure is the main contributor of roughly half of total GHG emissions if the main structural material is reinforced concrete. Exchanging reinforced concrete for a wood structure reduces total GHG emissions by 25%, with GHG emissions of the structure contributing 33% and windows 30%.” (Schneider-Marin et al., 2020) However, at early stage BDL, some overlap in results between building variants with a concrete structure and those with a wood structure can be identified. The results of this contribution analysis are validated against a simplified and a detailed calculation of the final design solution. The method correctly identifies the main drivers for energy use and GHG emissions.

“The study shows how a simplified and fast BIM-based calculation provides valuable guidance in early design stages.” (Schneider-Marin et al., 2020) It provides a basis for extension to LCC calculations and further elements of the building.

4.5 EarlyData Knowledge Base for Material Decisions in Building Design (Publication 5)

Schneider-Marin, Patricia; Stocker, Tanja; Abele, Oliver; Margesin, Manuel; Staudt, Johannes; Abualdenien, Jimmy; Lang, Werner (2022): EarlyData knowledge base for material decisions in building design. Advanced Engineering Informatics 54, 101769. DOI: 10.1016/j.aei.2022.101769

4.5.1 CRedit Author Statement

Patricia Schneider-Marin: Conceptualization; data curation; formal analysis; investigation; methodology; validation; visualization; writing – original draft; funding acquisition;
Tanja Stocker: Conceptualization; programming; writing - original draft;
Oliver Abele: Conceptualization; programming; writing - original draft;
Manuel Margesin; Visualization; writing – review and editing;
Johannes Staudt: Visualization; writing – review and editing;
Jimmy Abualdenien: Conceptualization; writing – review and editing;

Werner Lang: Funding acquisition; writing – review and editing;

4.5.2 Summary

This secondary publication addresses the problem that LCA data currently does not lend itself to easy application in design processes. LCA in design, if conducted at all, is the domain of LCA specialists who lack the necessary knowledge about the configuration of building parts. The designer, on the other hand, cannot judge the relevance of choosing one representative material over another in an early design stage. Hence, LCA data is generated with the production process of the material or product in mind, not with its applicability in a building. This means that information about relevant physical properties for design decisions (e.g., lambda values) and a categorization of building materials allowing for the selection of functionally equivalent materials are absent from life cycle inventory (LCI) data used as a basis for calculations. Moreover, single point emission values are calculated, suggesting a precision not representative for an early design stage.

The knowledge database developed in this study enriches existing material data by adding properties necessary for detailing. Information about possible locations and functions of materials within a building tied to LCI data, makes LCA accessible to non-experts. Thus, instead of single value results for a particular material combination, ranges of results are displayed guiding designers to the building parts with the greatest emission reduction potential. The database development is described in detail and the application of the related EarlyData tool is illustrated on a use case comparing a wood building and a concrete building.

The addition of cost data to enable LCA and LCC calculations in parallel is a planned further development of the knowledge database. The Eco^2 framework (Figure 7) and the data collection developed in publication 2 (section 4.2) can serve as a basis for this effort.

5 Discussion

The discussion of results is divided into the three sections, Eco² framework, environmental cost and decision making. First, advantages and weaknesses of Eco² are discussed, followed by lessons learned from the use of environmental cost to weigh and communicate LCA results, to conclude with implications for decision making in design processes.

5.1 Eco² Framework

The Eco² framework contributes to the integration of a life cycle perspective into the design process of buildings. It is based on the conviction that economic parameters cannot and should not be considered in isolation, following Mc Pherson's famous advice "If you think the economy is more important than the environment, try holding your breath while counting your money." (Mc Pherson, 2009). Eco² intends to introduce LCA and LCC into the decision-making process, and, with it, a value discussion necessary for designing buildings with a long-term perspective rather than short-term investment goals.

However, the case studies identified several data gaps and uncertainties potentially affecting the results of Eco² calculations, which could only partially be addressed in this study. Common data gaps include MEP systems, maintenance processes and end-of life processes and scenarios. Construction and demolition processes are less studied in LCA, whereas investment cost typically contains installation processes, but aggregated with material costs. For the case study, LCC methods, such as adding a percentage of the initial cost for recurring maintenance and repair, were transferred to LCA. This method needs to be further verified for the Eco² application. Moreover, cost data for end-of-life phases, including phase D, is lacking and available data shows a wide range. Currently ongoing discussions about circularity in the AEC sector bear the opportunity to fill this data gap.

Displaying results in a timeline reveals not only time and magnitude of environmental and economic impacts, but also the relationship between them. This ratio communicates the amount of environmental cost caused per monetary unit spent. Despite providing valuable information about the eco-efficiency of a particular solution, it should always be communicated in conjunction with the total environmental cost. Otherwise, it treats an expensive solution with high emissions equivalent to a cheap solution with low emissions, in effect neglecting the concept of sufficiency.

To enhance Eco², an extension to the scenario analysis conducted as part of this project for early design phases is necessary. In addition to varying temporal parameters, building sub-systems and environmental cost values as done in (Schneider-Marin & Lang, 2022), energy standards and more material choices need to be investigated, as well as uncertainties in service lives and end-of-life scenarios. Computer-based methods, Building Information Modelling (BIM) (Schneider-Marin et al., 2020) in conjunction with automated sample sets and data of lower granularity (Schneider-Marin et al., 2022b), show promising first results.

Buildings should have a positive impact rather than doing less damage. Therefore, the focus of LCA and LCC on environmental damage and financial cost is questionable – it should extend to including possible benefits. Unfortunately, this appears a difficult issue in environmental terms, because presently, too few buildings provide a service to the environment while providing people with comfort. New ways to design and operate buildings are needed that increase the quality of their surroundings and provide a benefit to their users and the ecosystems they are a part of.

5.2 Environmental Cost

The case studies in (Schneider-Marin & Lang, 2020) show a strong dependency of the environmental cost (EC) of buildings on two indicators: global warming potential (GWP) and abiotic resource depletion of elements (ADPE). Acidification (AP) plays a visible albeit minor role. Eutrophication (EP), ozone depletion (OPD) and photochemical ozone creation (POCP) contribute only marginally to total EC (see also section 4.1). The case study in (Schneider-Marin & Lang, 2022) extends this investigation to a range of material and energy supply alternatives with a similar outcome. This is in line with the perception that the AEC sector bears great opportunities to work towards the Paris goals to limit global warming. However, it also reveals that decisions made solely based on global warming potential as the environmental indicator might miss relevant other criteria.

High uncertainties occur in the absolute values of total environmental LCC. This is due to the high range of EC per unit emission, currently up to a factor of 28 for GHG emissions, responsible for the largest share of EC (Schneider-Marin & Lang, 2020). While a high range of values for GHG emissions has been calculated, cost data for resource depletion (ADPE) is lacking. Using the only value found in literature for the reference substance for ADPE (Sb-eq.) indicates that ADPE can have a great influence on total EC. Therefore, a thorough investigation into the external cost of resource depletion is necessary in order to open the discussion of the value of resources beyond their market price.

This study is limited to the set of five standard indicators currently used in Germany, with the addition of resource depletion. Therefore, the environmental costs calculated are not complete and the resulting weighting might shift when other indicators are included. Previous studies indicate, for instance, the additional relevance of toxicity, which could not be evaluated in the scope of this study because no data is available in Ökobaudat for this indicator. Therefore, the costs calculated in this study cannot be taken as “real” values but are likely to be underestimated.

Uncertainty about the total amount of global emissions, i.e., the state of the environment, and therefore the relevance of future emissions aggravates the uncertainties in valuation. On the one hand, this inaccuracy stems from the current data for buildings: With the exception of data for the electricity mix, no data sets are available that account for scenarios of future energy supply or production technologies. On the other hand, the future significance of emissions is uncertain as it depends on the overall environmental load. Publication 3 (Schneider-Marin & Lang, 2022) shows the effect of applying time parameters, discounting and price change, to future (monetized) emissions. It is striking how these parameters change the ranking in the choice of alternative construction materials, especially if end-of-life emissions are high. Therefore, they should be included and discussed in design processes. Although time preference can depend on the individual project and stakeholder perspective, a consensus needs to be found on the range of price changes and discount rates that should be considered. In this study, the same price change rates for environmental cost and energy prices were used but the common discount rate for emissions (0%) was applied and varied. These values and their interdependencies should be discussed and defined further.

In light of the increasing urgency of limiting greenhouse gas emissions, the case study results lean towards a recommendation of a discount rate for emissions over the life cycle to prioritize emissions savings now and thereby underline the importance of immediate action. This is counterintuitive to intergenerational equality, i.e., it might suggest that it discriminates against future generations by downplaying the significance of future emissions. However, this criticism should bear in mind that discounting does not apply to the emissions directly, but to their monetary value, which is subject to similar market mechanisms (including price increase) as market prices. Discounting in this context has a similar effect as dynamic LCA, if it restricts the time horizon for the effect of emissions to the study period. It finds delayed emissions are preferable to immediate emissions (Resch et al., 2021).

The AEC sector has been identified as a sector for cost-efficient CO_2-abatement. However, looking closely at sectoral CO_2-abatement curves, all measures listed for buildings pertain to the operational phase B6 (Mc Kinsey & Company, 2009). This raises the question if CO_2-emissions saving in building materials is a valid option. As mentioned in section 2.3.1, the AEC sector is not an economic sector in the narrow definition. Therefore, emissions saving opportunities pertaining to the embedded emissions of the AEC sector are located in other sectors (e.g., cement, iron and steel, transport). Such sectoral emissions saving measures would reduce construction material emissions without requiring the use of alternative materials in building design. At the same time, buildings have been identified as potential carbon storage or carbon sinks (Churkina et al., 2020; Pomponi et al., 2020), if mineral materials are replaced by plant materials (mainly wood and bamboo), provided that forests and plantations are sustainably managed.

In building design, the question arises, if it is economically viable to save emissions by replacing an emission-intense material by a low-emission material. In other words, if internalization of external costs via subsidies or taxes makes low-emission materials economically competitive. Internalization by taxes follows the “polluter-pays-principle” by making emission-intense products more expensive, essentially increasing overall construction prices. Preliminary studies from several master’s thesis projects indicate that large-scale replacement of mineral construction materials by renewable materials (wood, straw etc.) is by far not an economically favourable option. The results consistently determine high abatement costs of 300 € (Matuschek, 2021), 2.300 € (Ries, 2021) up to 2.700 € (Winklmann, 2020) per ton of CO_2-eq, if abatement is achieved by material replacement. This indicates that, firstly, replacing building materials might exceed marginal abatement costs. Secondly, emissions savings might be too narrow a criterion. It neglects the fact that natural cycles fundamentally differ from technological cycles, because the limit to biogenic material use is their natural regrowth rate while fossil material supply is limited to the current resources without replenishment. Therefore, it might not be sufficient to tax emissions, but further incentives for renewable material use need to be considered.

Most likely the greatest limitation of using monetary valuation to weigh and communicate environmental impacts is the fact that currency values do not provide a measure of the relevance of the impact in relation to the carrying capacity of the ecosystem. Monetary valuation, however, can take this into account in different ways. First, marginal prevention costs should be established based on the maximum emissions tolerable by ecosystems. Ideally, all measures of emissions savings below this cost value would then be taken, because paying for the external cost would prove to be more expensive. Secondly, willingness to pay for improved quality could be established for buildings, not only for environmental qualities, but also for less even tangible spatial or architectural qualities. Such willingness to pay values can help decision makers to gauge the value of buildings with positive impacts. Despite its benefits, monetary valuation should not be the one and only solution to weighing different criteria, as it might over-simplify the complexity of buildings and ecosystems. A discussion about the value and benefits as compared to potential damages and side-effects of buildings should be part of every design process.

5.3 Design Decision Making

The Eco² framework is intended for use in decision making processes for building design. Such processes typically involve many different stakeholders, from the owner of a single home to large property holding companies or public authorities. Each stakeholder group has a specific implicit or explicit time-horizon, which may vastly differ from the standard 50-year study period. Representing the results in timelines can help to integrate these different time horizons and to communicate the value of a building during its life cycle to potential buyers. Additionally, other result representation methods should be investigated to test their applicability in design processes. Moreover, the time preference of multiple stakeholders should be considered in scenario creation.

Stakeholders consider a multitude of different criteria in a design process. Budgetary criteria and legal requirements are certainly amongst them, but environmental criteria might not be part of the decision making. Considering them in parallel with budgetary constraints bears the great opportunity of the communication and inclusion of environmental criteria. At the same time, win-win solutions can be identified with simultaneous low cost and low environmental impact. The representation of trade-offs respects budgetary constraints, counteracting the perception that environmental considerations are only for rich idealists. Additionally, the communication of external costs makes it obvious that a cheap, environmentally damaging, short-term solution will have to be paid for by society as a whole and / or future generations. This also provides information to policymakers on where external costs should be internalized to avoid damages somewhere else or at another point in time.

The case study showed that adding eLCC to fLCC has the potential to tip the scale from solutions with the lowest fLCC towards solutions with lower eLCC. However, a large part of fLCC occurs in the future, making these costs less certain and less tangible than investment costs, which are typically a decisive criterion in design decisions. Hence, considering fLCC in lieu of investment costs is already an improvement to a standard design process because it includes a life cycle perspective. Now, adding the environmental perspective will be a challenge as it adds to multiple requirements and constraints. Therefore, underlying calculations should be as easy to implement as possible.

The Eco² framework provides an opportunity to limit calculation efforts as only one life cycle inventory and corresponding base data needs to be established, saving time and effort in comparison to separate LCA and LCC calculations. The framework was developed with LCA as the underlying method, as LCA is a standardized and well-established method. This could also be done the other way around by attaching environmental data to costs making environmental impact calculations essentially a by-product of cost calculations.

This project is limited to environmental and economic life cycle assessments. Local environmental and economic effects (e.g., indoor environmental quality, effects of buildings on an urban scale) are not included. The social and cultural dimension of sustainability is only touched upon, but not considered in depth. Therefore, it is an input to sustainability considerations in design processes, but not a full sustainability assessment.

6 Conclusion and Outlook

The answers to the research questions summarize the key results of this study. Finally, areas for further research are described.

6.1 Summary of Key Results

The key results of the study provide answers to the research questions in order to enable environmental and economic evaluations of building design solutions. Table 7 shows the relevance of each publication to the research questions.

Table 7: Research questions and publications; (x) means that the literature search provided information about the state of the art.

	Research question	Publication				
		1	2	3	4	5
1	Integration of environmental and economic factors into building design?		x	x		
2	Weighting by monetary valuation?	x	(x)	x		x
3	Relationship between environmental and economic impacts?	x	(x)	x		
4	Temporal factors?		(x)	x	x	

6.1.1 How can environmental and economic factors be integrated into building design?

LCA and LCC are well-established methods to evaluate environmental and economic performance throughout the life cycle of a building, but their individual application in design processes is limited, while their integrated use is virtually non-existent in practice in the AEC sector. To make the best use of the opportunities in a harmonized application, the Eco^2 framework recommends using a single life cycle inventory for environmental and economic factors, aligning temporal and spatial system boundaries as well as scenario analyses, and integrating results. Common ground can be found in

- the definition of life cycle phases,
- the classification of building subsystems,
- a number of parallel steps:
    - goal and scope definition
    - inventory analysis
    - impact analysis
    - interpretation and communication of results.

Great opportunities lie in the enrichment of environmental background data with economic information and associating environmental impacts to financial costs. This reveals how environmental and economic impacts are linked and enables stakeholders to identify win-win situations where environmental and economic impacts are turned into profits.

6.1.2 Does monetary valuation provide a consistent weighting of building LCA results? If so, which environmental indicators are relevant for buildings according to monetary valuation?

For result integration of economic and environmental impacts, environmental impacts can be turned into currency, so that they can be summarized to a single result value and provide a counterweight to economic considerations. The analysis of Ökobaudat data and the applications to a case study with 6 office buildings and a case study with many variations of one office building shows that monetary valuation consistently weighs GWP the most relevant mid-point impact category. This is entirely unequivocal for energy use in building operation. If fossil fuels are the main energy carrier, on average 91% or 97% of environmental cost are associated with GWP, depending on the monetary valuation set used. For the building's structure and finishes, GWP is responsible for 80% to 95% of the overall environmental cost of a sample set of office buildings, with AP the second largest contributor (4% to 18%). The environmental cost of MEP systems, however, is not only influenced by GWP (on average 58% or 63%), but also strongly by ADPE (28% or 33% for low / high valuation).

Therefore, monetary valuation does provide consistent weighting for the set of indicators considered (GWP, AP, EP, POCO, ODP, APDE), independent of the valuation set. However, the overall quantity of environmental cost depends strongly on the valuation of the most relevant indicators, GWP, ADPE and AP.

6.1.3 What is the relationship between environmental and economic impacts of buildings?

The ratio between eLCC and fLCC of buildings does not only depend strongly on the valuation system used, but also on discounting and price changes rates for economic and environmental impacts.

In the initial study using standard static LCA (Schneider-Marin & Lang, 2020), eLCC of structure and finishes at the minimum valuation are almost imperceptible compared to fLCC, accounting for a mere 1%. This does not reflect the perceived high relevance of the AEC sector for global emissions and resource consumption. Moreover, it raises doubts that the price tag currently assigned to greenhouse gas emissions in compensation schemes, 25 € per ton of CO_2-eq., which was the basis for this evaluation, can be an incentive to lower emissions. At the highest valuation, 640 € per ton of CO_2-eq., eLCC are up to 37% of fLCC.

The application of the Eco² framework to the second case study (Schneider-Marin & Lang, 2022) uses a quasi-dynamic approach with price increase and discounting. This shows a higher ratio of eLCC to fLCC for CG 300 (structure and finishes), between 14% and 157% in the standard scenario at medium valuation of impacts. The highest ratio is caused by price changes for environmental cost, as the solution in question has a high wood content incurring high costs in the end-of-life stage. If only phase C is taken into account, excluding phase D, greenhouse gases emitted by the burning of wood at the end of the building's service life are subject to the exponential effect of 50 years of price increase. This does not only put into question the end-of-life scenario of wood, but also the static approach of crediting carbon sequestration in life cycle phase A1 and accounting for emitted carbon in life cycle phase C3, commonly known as the -1/+1 approach (Hoxha et al., 2020b). In this context, dynamic methods of accounting for biogenic carbon should be considered, e.g., taking into account the carbon uptake of trees during the building's service life in sustainably managed forests.

For the building's MEP systems and building operation, eLCC are higher than for CG 300, between 65% and 357% in the standard scenario for medium evaluation of impacts. For the MEP systems, too, the inclusion or exclusion of phase D plays a considerable role, as MEP systems contain metals and other resource intense materials with high recycling potential. In the low time preference scenario at minimum valuation of impacts, including phase D accounts for end-of-life credits and even results in a net environmental cost gain. For higher valuation of impacts and low time preference, solutions with fossil energy carriers cause eLCC of up to 762% of fLCC. As the eLCC of CG 400 and building energy use surpass the fLCC, they offer cost-efficient saving opportunities. Replacing fossil energy carriers with renewable options can save a high amount of eLCC at a low life cycle cost premium.

6.1.4 (How) can building LCA include temporal factors in parallel to LCC?

Dynamic LCA includes temporal factors, but it requires dynamic life cycle inventory data. Such data is currently available in Ökobaudat only for the German electricity mix. These datasets were taken into account in the case study, lowering the overall eLCC of electricity use. As dynamic data is currently not available for building products, the quasi-dynamic approach is transferred from LCC to environmental costs, using constant discount rates to account for future uncertainties and price change rates to account for increases in avoidance, damage, or mitigation cost. This enables stakeholders to see the effect of time preference and market changes on eLCC.

Rates from LCC are used in LCA, because no standard values for these factors are available for eLCC. The scenario analysis used the same price change rates as for energy price change. The standard scenario includes a 0 % discount rate for eLCC, as standard LCA currently does not consider discounting. This rate is changed to 1,5 % and – 1,5% in the high time preference and low preference scenario respectively.

The high time preference scenario favours delaying emissions (e.g., by carbon storage), whereas the low time preference scenario prefers to emit now, in order to save emissions at a later point in time (e.g., investing emissions in photovoltaics). Time preference has great influence on the weight of end-of-life emissions, as these emissions occur when the exponential effect of constant price change and discount rates have their full effect.

The quasi-dynamic approach offers valuable insights regarding future emissions and provides the possibility to consider dynamic effects when dynamic LCI data is not available. Seeing the striking effect of varying discount and price change rates, a scenario analysis should always be included to enable a discussion about the weight of future emissions versus the urgency to immediately cut emissions.

6.2 Methodological Contributions and Practical Value

The Eco² method draws on the existing LCA and LCC framework and synchronises and aligns current discrepancies. By using costs as the unit of evaluation, it provides a familiar basis for decisions facilitating the integration into the design process. As such, harmonized environmental and economic life cycle considerations provide a useful basis for design decisions. In this process, monetary valuation of environmental impacts is an applicable weighting method for building LCA. Juxtaposing LCA results converted to monetary units and LCC results reveals win-win opportunities providing environmental improvements at no extra cost or at a financial benefit.

Eco² provides the basis for increasing usability of life cycle considerations in design processes. It reveals the need for providing environmental and cost data in one database, either complementing cost data with environmental impacts, or vice versa. The most promising approach is to use both, cost and environmental data, to identify and fill data gaps. A complete database would make the method relatively easy to implement with little additional effort. Additionally, result representation in timelines opens the life cycle perspective.

The most relevant life cycle phases for LCA and LCC were identified in the process. This shows that for some life cycle phases, LCA and LCC can be treated as almost independent, when either economic or environmental impacts are low compared to the other. One example would be cleaning (life cycle phase B2), where environmental impacts are almost negligible, whereas financial impacts can be high. This also showed and stressed the relevance of end-of-life scenarios and the impact of inclusion or exclusion of phase D.

Finally, using temporal parameters in LCA to this extent has not been considered in previous studies. Applying price change and discount rates to environmental costs has proven to reveal the impact of differing time preferences. This, unlike static LCA, has the potential to show the effect of delaying emissions and taking into account the point in time when emissions occur.

6.3 Implications for Policy and Research

Future research should refine environmental cost calculations for resource depletion (ADPE), as few data is available for this indicator although it has proven relevant for buildings. In addition, environmental impact data and monetary valuation on the toxicity of building materials is missing despite its potential relevance for buildings. Generally, research efforts should ensure aligned characterization and monetary valuation models such that impact assessment paths are consistent throughout life cycle impact assessment (LCIA). Additional data gaps concern MEP systems and the environmental and economic evaluation of the end-of-life phases of buildings. Environmental cost calculations consider social impacts to a certain degree, if environmental degradation has effects on society (e.g., health). As such, they bear the opportunity to extend these calculations to social LCA (SLCA), to gain an understanding of “soft” criteria by making them more tangible.

Opportunities for further development of Eco² building evaluation lie in making the method more dynamic. Temporal parameters from economic methods, discount and price change rates, provide a basis for introducing dynamic aspects into LCA. Additionally, taking into account the changing electricity mix in Germany over time has a visible effect for the use phase of buildings. The method would benefit from extended life cycle inventory data for building materials containing scenarios for future energy supply for production processes and for material scarcity, as well as end-of-life scenarios in addition to the currently provided single standard scenario.

We used a number of non-residential office and administration buildings as case studies. Therefore, the results are most accurate for this building type. Extending the investigation to other non-residential and residential buildings might reveal differing tendencies for other building types, while confirming the importance of GWP and of including environmental criteria in design processes currently dominated by cost discussions. The case study in (Schneider-Marin & Lang, 2022) investigates CG 300 and CG 400 + life cycle phase B6 independently to analyse the differences between building sub-systems. This investigation should be extended to take into account their mutual influence. This entails varying the heat distribution and transfer systems in the building as well as replacing static energy calculations by dynamic simulation to be able to analyse the effect of material properties such as thermal mass on building energy use. Additional renewable energy supply scenarios would complete the picture.

Uncertainties and related sensitivity analyses provide another research area with high potential. In conjunction with digital methods, they contribute to increasing robustness and credibility of Eco^2 analyses. First investigations indicate that uncertainties are reference service lives, design uncertainties (geometry, material choices), and end-of-life processes, as well as monetary valuation values and temporal parameters.

This research focussed on process-based LCA and LCC. However, environmentally extended economic input-output analysis (EIOA) could contribute a more comprehensive picture of sector-wide or economy-wide impacts of single buildings. Disaggregation of this data to support material choices will most likely have to stop at a degree of granularity that is more applicable to early design phases. Like this, it could complement process-based Eco^2 for later design phases. Additionally, material flow cost accounting (MFCA) should be applied to building materials and buildings to gain a more thorough understanding of inefficiencies and areas of improvement.

Future policies should include external costs for public procurement to provide a measure of communicating the environmental value of a building project. This could stimulate more research into monetary valuation and stir a discussion about the allocation of financial and environmental costs and benefits. On a building product level, products with a high ratio of eLCC to fLCC could be considered for emissions tax to decrease their economic attractiveness, which currently is achieved at the expense of society. However, this should not happen without a value discussion on priorities and about environmental cost models used, to avoid that such costs are taken at face value and suggest that all potential negative effects are included and can be compensated for by financial payments.

6.4 Final Remarks

This project started with a quest to make environmental indicators more accessible and comprehensive for design processes. Monetary valuation of environmental impacts includes all indicators under consideration and provides a familiar unit, currency, for evaluation. It assigns a value to emissions opening up the discussion about external costs. Crossing the border from environment to economy requires including “real” financial cost in the picture, concluding that LCA and LCC should always be considered in parallel. More importantly, fLCC should not be the only cost value discussed in design processes. Even though an investor does not pay for the external cost, displaying this cost value is useful as it reveals the costs paid by someone else, who might not receive any benefits from the project in question. Moreover, adding eLCC to fLCC for total life cycle cost has the potential to tip the scale towards solutions with low environmental cost.

Adding the time horizon to environmental-economic calculations highly influences results and, thereby, the basis for decisions. This should not be disregarded as too uncertain but grasped as a chance to be more precise about what it means to stakeholders to build “sustainably” for future generations.

Funding

Funding for this project was provided through the Design2Eco project by the Bundesministerium des Innern, für Bau und Heimat, Germany, under grant number SWD10.08.18.7.-16.60, and from ATP Planungs- und Beteiligungs- AG, BayWa AG, and Stiftung Bayerisches Baugewerbe. Through the EarlyBIM project, funding was provided by the Deutsche Forschungsgemeinschaft (German Research Foundation, DFG) under grant FOR2363 (project number 271444440). Open Access for publication 1 was provided by the project DEAL.

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DIN EN 15643-1:2010-12 Nachhaltigkeit von Bauwerken – Bewertung der Nachhaltigkeit von Gebäuden – Teil 1: Allgemeine Rahmenbedingungen; Sustainability of construction works – Sustainability assessment of buildings – Part 1: General framework;

DIN EN 15643-2:2011-05 Nachhaltigkeit von Bauwerken – Bewertung der Nachhaltigkeit von Gebäuden – Teil 2: Rahmenbedingungen für die Bewertung der umweltbezogenen Qualität; Sustainability of construction works – Assessment of buildings – Part 2: Framework for the assessment of environmental performance;

DIN EN 15643-3:2012-04 Nachhaltigkeit von Bauwerken - Bewertung der Nachhaltigkeit von Gebäuden - Teil 3: Rahmenbedingungen für die Bewertung der sozialen Qualität; Sustainability of construction works - Assessment of buildings - Part 3: Framework for the assessment of social performance.

DIN EN 15643-4:2012-04 Nachhaltigkeit von Bauwerken – Bewertung der Nachhaltigkeit von Gebäuden – Teil 4: Rahmenbedingungen für die Bewertung der ökonomischen Qualität; Sustainability of construction works – Assessment of buildings – Part 4: Framework for the assessment of economic performance;

DIN EN 15643-5:2018-05 Nachhaltigkeit von Bauwerken – Bewertung der Nachhaltigkeit von Gebäuden und Ingenieurbauwerken – Teil 5: Leitfaden zu den Grundsätzen für und den Anforderungen an Ingenieurbauwerke; Sustainability of construction works – Sustainability assessment of buildings and civil engineering works – Part 5: Framework on specific principles and requirement for civil engineering works;

DIN EN 15804:2014-07 Nachhaltigkeit von Bauwerken - Umweltproduktdeklarationen - Grundregeln für die Produktkategorie Bauprodukte; Sustainability of construction works – Environmental product declarations – Core rules for the product category of construction products;. Online verfügbar unter DOI: https://dx.doi.org/10.31030/2074465, zuletzt geprüft am 06.11.2019.

DIN EN 15804:2020-03 Nachhaltigkeit von Bauwerken - Umweltproduktdeklarationen - Grundregeln für die Produktkategorie Bauprodukte; Sustainability of construction works – Environmental product declarations – Core rules for the product category of construction products;

DIN EN 15978:2012-10: Nachhaltigkeit von Bauwerken - Bewertung der umweltbezogenen Qualität von Gebäuden - Berechnungsmethode; Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method;

DIN EN 16627:2015-09 Nachhaltigkeit von Bauwerken - Bewertung der ökonomischen Qualität von Gebäuden - Berechnungsmethoden; Sustainability of construction works – Assessment of economic performance of buildings – Calculation methods;

DIN EN 60300-3-3:2005-03 Zuverlässigkeitsmanagement - Teil 3.3: Anwendungsleitfaden - Lebenszykluskosten (IEC 60300-3-3:2004); Dependability management - Part 3.3: Application guide - Life cycle costing.

DIN EN ISO 14040:2009-11 Umweltmanagement - Ökobilanz - Grundsätze und Rahmenbedingungen; Environmental management - Life cycle assessment - Principles and framework. Online verfügbar unter DOI: https://dx.doi.org/10.31030/1555059, zuletzt geprüft am 06.11.2019.

DIN EN ISO 14044:2006-10 Umweltmanagement – Ökobilanz – Anforderungen und Anleitungen; Environmental management – Life cycle assessment - Requirements and guidelines.

ISO 14008:2019-03 Monetary valuation of environmental impacts and related environmental aspects.

ISO 15686-1:2011-05 Buildings and constructed assets - service life planning; Part 1: general principles and framework.

ISO 15686-2: 2012-06 Buildings and constructed assets - service life planning; Part 2: service life prediction procedures.

ISO 15686-4:2014-01 Buildings and constructed assets - service life planning; Part 4: Service life planning using Building Information Modelling.

ISO 15686-5:2017-07 Buildings and constructed assets - service life planning; Part 5: Life-cycle-costing.

ISO 15686-6:2004-09 Buildings and constructed assets - service life planning; Part 6: Procedures for considering environmental impacts - WITHDRAWN

ISO 15686-7:2017-04 Buildings and constructed assets - service life planning; Part 7: performance evaluation for feedback of service life data from practice.

A Appendix

A.1 Life Cycle Impact Assessment Methods

Table 8: LCIA methods (EC JRC, 2010; M. A. J. Huijbregts et al., 2016; Ministry of Housing, Spatial Planning and the Environment, The Netherlands, 2000)

LCIA Method	Mid-Points	End-Points	Weighting method	Single indica-tor?
CML2002	ADPE Land Competition GWP ODP Human Toxicity Freshwater Aquatic Ecotoxicity Marine Aquatic Ecotoxicity Terrestrial Ecotoxicity POCP AP EP (Additional Impact Categories available)	None	None	No
Eco-Indica-tor99	(not separated -> end-points) GWP ODP AP/EP (combined) Carcinogenic Respiratory Organic Ionizing Radiation Ecotoxicity Land-use Mineral Resources Fossil Resources	Human Health Ecosystem Quality Resource Depletion	Damage Function	Yes (Eco-In-dicator Points)
ReCiPe (fol-low-up to CML2002 and Eco-Indica-tor99)	climate change ODP ionising radiation fine particulate matter formation POCP terrestrial acidification freshwater eutrophication marine eutrophication; toxicity water use land use mineral resource scarcity fossil resource scarcity	Human health ecosystem quality resources (surplus cost)	Perspectives: Individualist Hierarchist Egalitarian	No
EDIP97 and EDIP2003	GWP ODP AP Nutrient Enrichment (EP) POCP Human Toxicity (4 sub-categories) Ecotoxicity (4 sub-categories) Resources Working Environment (7 sub-categories)	None	Distance to (political) tar-get	No

EPS2000	Life expectancy Severe morbidity and suffering Morbidity Severe nuisance Nuisance Crop production capacity Wood production capacity Fish and meat production capacity Base Cation capacity Production capacity for water Share of species extinction Depletion of element reserves Depletion of fossil reserves Depletion of mineral reserves	Human health Ecosystem production Biodiversity Abiotic Stock resource	Monetary valuation (WTP: revealed preferences and restoration costs)	Yes Env. Load Units (ELU)
Impact 2002+	Human toxicity Respiratory effects Ionizing radiation ODP POCP Aquatic ecotoxicity Terrestrial ecotoxicity Aquatic eutrophication Terrestrial eutrophication and acidification Land occupation GWP Non renewable Energy Mineral extraction	human health ecosystem quality climate change resources	None	No
LIME	Urban air pollution GWP ODP Human Toxicity Eco-toxicity AP EP POCP Land Use Consumption of minerals Consumption of energy Consumption of biotic resource Indoor air pollution Noise Waste	Thermal stress Malaria Infectious diseases starvation natural disasters Cataract Skin cancer Other cancer Respiratory defects Biodiversity (terrestrial) Biodiversity (aquatic) Plant Benthos Fishery Crop Materials Mineral Resources Energy resources -> These category endpoints are linked to four "safeguard subjects" Human health Social welfare Biodiversity Primary production	Monetary valuation Societal Costs	Yes (¥)
LUCAS	GWP ODP AP POCP Respiratory effects Aquatic eutrophication Terrestrial eutrophication Ecotoxicity (aquatic and terrestrial) Human toxicity Land-use ADP	None	None	No

Ecological Scarcity Method (Ecopoints)	GWP ODP POCP Respiratory effects Surface water emissions. Cancer caused by radionuclides emitted to the sea Emissions to groundwater Emissions to soil Waste Water consumption Gravel consumption Primary energy resources Endocrine disruptors Biodiversity losses due to land occupation	None	Distance to Target	Yes (UBP)
TRACI	ODP GWP Smog formation AP EP Human health cancer Human health noncancer Human health criteria pollutants Eco-toxicity Fossil fuel depletion	None	None	No
MEEup	Energy Water Waste Emissions to air GWP ODP AP POP VOC Heavy Metals Human health Particulate matter Emissions to water	None	None	No
USETox	Human toxicity Ecotoxicity (Respiratory effects Indoor emissions)	Human Health Ecosystem Quality	None	No
EcoSense (ExternE, NEEDS, CASES)	POCP AP EP respiratory inorganics (no characterization factors)	None	None	No
Ecological Footprint	None	Land Use Climate Change (not explicit)	None	Yes (Gha)

A.2 Publications

Publication 1: Schneider-Marin, P., & Lang, W. (2020). Environmental costs of buildings: monetary valuation of ecological indicators for the building industry. The International Journal of Life Cycle Assessment, 25(9), 1637–1659. https://doi.org/10.1007/s11367-020-01784-y

Publication 2: Schneider-Marin, P., Winkelkotte, A., & Lang, W. (2022a). Integrating Environmental and Economic Perspectives in Building Design. Sustainability, 14(8), 4637. https://doi.org/10.3390/su14084637

Publication 3: Schneider-Marin, P., & Lang, W. (2022). A Temporal Perspective in Eco2 Building Design. Sustainability, 14(10), 6025. https://doi.org/10.3390/su14106025

Publication 4: Schneider-Marin, P., Harter, H., Tkachuk, K., & Lang, W. (2020). Uncertainty Analysis of Embedded Energy and Greenhouse Gas Emissions Using BIM in Early Design. Sustainability, 7(12), Article 2633. https://doi.org/10.3390/su12072633

Publication 5: Schneider-Marin, P., Stocker, T., Abele, O., Margesin, M., Staudt, J., Abualdenien, J., & Lang, W. (2022b). EarlyData knowledge base for material decisions in building design. Advanced Engineering Informatics, 54, 101769. https://doi.org/10.1016/j.aei.2022.101769

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The International Journal of Life Cycle Assessment
https://doi.org/10.1007/s11367-020-01784-y

BUILDING COMPONENTS AND BUILDINGS

Environmental costs of buildings: monetary valuation of ecological indicators for the building industry

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Received: 20 March 2020 / Accepted: 22 June 2020

Abstract

Purpose Building life cycle assessment (LCA) draws on a number of indicators, including primary energy (PE) demand and global warming potential (GWP). A method of constructing a composite index of weighted individual indicators facilitates their use in comparisons and optimization of buildings, but a standard for weighting has not been established. This study investigates the use of monetary valuation of building LCA results as a way to weigh, aggregate, and compare results.

Methods A set of six recent German office buildings served as a case study. For these, standard LCA and life cycle cost (LCC) calculations were conducted. Monetary valuation models from the literature were investigated as a basis for evaluation. From these, maximum and minimum valuation was chosen and applied to the LCA results for the embedded impacts of the case study buildings. The buildings' environmental costs (EC) were thereafter calculated and contributions of single impacts are analyzed. The EC—based on external costs—are subsequently compared with the life cycle costs (LCC)—based on market prices—of the respective buildings.

Results and discussion Of the five standard environmental indicators used in Germany, GWP contributes approximately 80 to 95% of the overall EC. Acidification potential (AP) is the second largest contributor with up to 18%. Eutrophication (EP), photochemical oxidization (POCP), and ozone depletion potential (ODP) contribute less than 2.0%, 1.05%, and 2.4E−6% respectively. An additional assessment of the contribution of resource depletion to EC shows an impact at least as large as the impact of GWP. The relation between the EC and LCC strongly depends on the EC model used: if EC are internalized, they add between 1 and 37% to the life cycle costs of the buildings. Varying construction materials for a case study building shows that materials with low GWP have the potential to lower environmental costs significantly without a trade-off in favor of other indicators.

Conclusions Despite their sensitivity to the monetary valuation model used, EC provide an indication that GWP and resource depletion—followed by AP—are the most relevant of the environmental indicators currently considered for the construction industry. Monetary valuation of environmental impacts is a valuable tool for comparisons of different buildings and design options and provides an effective and valuable way of communicating LCA results to stakeholders.

Keywords Building life cycle assessment · LCA · Monetary valuation of environmental impacts · Environmental life cycle cost · Weighting in LCA · Comparative LCA · Building life cycle cost · LCC

1 Introduction and problem statement

The building industry is one of the major contributors to climate change and the consumption of the earth's resources. In this context, life cycle assessment (LCA) is being established as a method of evaluating the environmental quality of buildings (Weissenberger et al. 2014), as it assesses environmental impact for their entire life cycle. As the use of life cycle assessment (LCA) is adapted to buildings, it is facing multiple challenges. Originally, LCA was designed for evaluating and optimizing industrial products (Klöpffer and Grahl 2009) that are usually made in batch production. Buildings, on the contrary, are almost exclusively prototypes and consist of a multitude of products and services. Hence, each individual

Responsible editor: Holger Wallbaum

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s11367-020-01784-y) contains supplementary material, which is available to authorized users.

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Published online: 27 July 2020

building needs a custom LCA, requiring detailed knowledge about the building in question. To simplify building LCAs, they are, with very few exceptions, calculated on the basis of aggregated product data in lieu of single processes, as LCA calculations would otherwise demand too much time, be open to calculation errors, and lack comparability.

In Germany, building LCA calculations use the publicly available database Ökobaudat (Bundesministerium des Innern, für Bau und Heimat (BMI) 2016). This database contains LCI (life cycle inventory) and LCIA (life cycle impact assessment) data for over 1000 different building products and building-related processes. Each product or process is evaluated in terms of 8 input categories (e.g., energy, material), 8 output categories (e.g., exported energy, waste), and 7 environmental impact categories (e.g., global warming potential (GWP), acidification potential (AP)). The choice of indicators contained in Ökobaudat originates from LCA's original application in product development. Therefore, it might not reflect those environmental problems for which the building industry is most relevant for, but is simply a consequence of data availability.

Consequently, the full results of building LCA studies containing all individual 23 indicators are difficult to comprehend for stakeholders in the building industry. The multitude of indicators does not lend itself readily to decision-making in the planning process as the indicators show a variety of issues: various environmental problems, resource consumption, and waste generation. These are measured in terms of incommensurable units and, in addition, might show very different tendencies depending on the building materials used. Therefore, results for different indicators often contradict each other. Overall optimization is thus impossible when different indicators do not share a common measure of evaluation and move independently of one another.

A widely used work-around is restricting the assessment to one or a few indicators that are deemed most crucial, for instance, global warming potential and/or primary energy use (non-renewable/renewable). The obvious downside is that other potentially important environmental impacts are ignored and trade-offs involving them cannot be considered (Ströbele 2013).

The nature of the building design process requires multi-criteria decision-making support and optimization of many aspects such as structural safety, fire safety, and costs. In such an inevitably complex context especially, a simple, readily comprehensible, single indicator of environmental impacts would enable decision-makers to take such impacts into consideration—where, in the absence of such an indicator, environmental impacts, for practical reasons, often are ignored, in part or entirely. In this regard, Kägi et al. (2016) argue that there is a "need for end-point or single-score assessment (and transparent communication of the same) for sound and effective decision-making support."

The basic structure and rules for LCA are specified in DIN EN ISO 14040 and DIN EN ISO 14044. DIN EN ISO 14044 does not allow for a weighting of indicators in publicly available comparative LCA studies (DIN Deutsches Institut für Normung e.V. 2009). Nevertheless, several methods provide end-point and/or single-score conversion of LCA results in order to make indicators commensurable and thereby LCA results comparable and easier to understand for stakeholders (Pizzol et al. 2017). The weighting step is a value choice of the stakeholders and hence has to be carefully considered (Steen 2006; Bengtsson and Steen 2000). End-point systems, such as ReCiPe (Goedkoop et al. 2013) or UBP (Ahbe 2014), establish a scoring system that assesses the potential damage (or benefit) to humans, ecosystems, and resources. Building certification systems, such as the DGNB[1] system, assign percentage values to the indicators, e.g., 40% to GWP. These percentage values are choices of the respective certification system and reflect the relative importance of an indicator assigned by the certification organization. Single-score systems aggregate either LCIA data and/or mid-point indicators, e.g., the Austrian OI3 (IBO—Österreichisches Institut für Bauen und Ökologie GmbH 2016), or end-point indicators to a single value allowing comparison of options.

Monetary valuation of LCA results (Fig. 1) is such a single-score indicator method that is increasingly used by stakeholders, as it provides ecological costs (EC) as an easy-to-understand basis for decisions. Its main critique is that it is regarded as questionable from a sustainability accounting point of view: assigning monetary values to environmental problems might suggest that by paying for the "cost" of the pollution, it is possible to compensate for the impact of the pollution in question (Vogtländer and Bijma 2000). It is thus criticized to be an instrument of "weak" sustainability, as it suggests that monetary means can compensate for the loss of ecological quality (Rennings and Wiggering 1997). Monetary valuation methods should take this critique seriously and always reveal their background and purpose.

Monetary valuation's advantage is that it can provide valuable information to stakeholders and policy makers when assessing the overall environmental quality of projects, products, or services (Swarr et al. 2011). In addition, monetary valuation facilitates comparing EC to current market prices of products and services. Moreover, assigning monetary values to environmental factors enables environmental criteria to be taken into account in business decisions (Reid et al. 2005) and it can be applied in cost-benefit analyses.

None of the existing monetary valuation methods is specifically geared towards LCA in the building industry. Adensam et al. (2002) have previously studied monetary valuation of environmental impacts of buildings applying (fixed) cost

[1] Deutsche Gesellschaft für nachhaltiges Bauen; German Sustainable Building Council

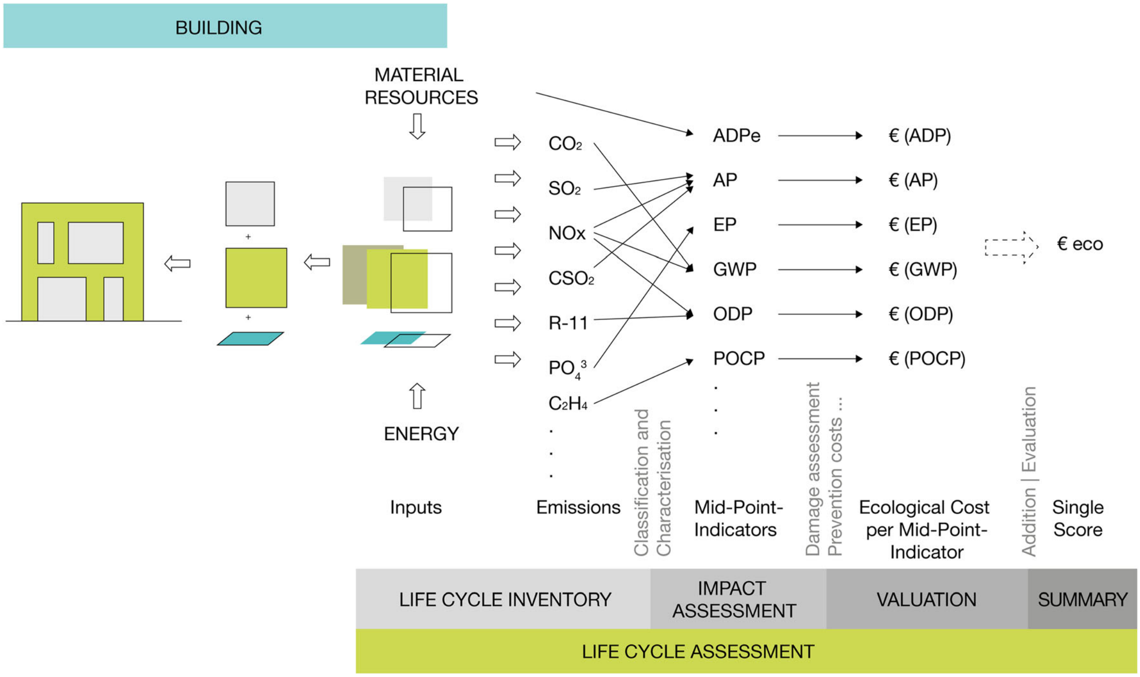

Fig. 1 Building LCA and monetary valuation of mid-point indicators to arrive at a single score

parameters to two sample projects. The study concludes that the external costs of the building materials amount to approximately 3% of the two sample buildings' construction cost and that, based on the Austrian database used, CO_2 pricing has the greatest influence. Ulmer et al. (2010) take their valuations for ODP, POCP, and EP from Adensam et al. (2002) and use Friedrich et al. (2007) valuations of AP and GWP in their study of six (residential) sample projects. They conclude that internalizing external costs increases construction costs by an average of approximately 35%, differing from Adensam et al. (2002) by a factor of more than 10. This is in part due to the fact that primary energy demand is valued in addition to environmental indicators, but, to a larger extent, including the external costs for the energy demand during building operation (phase B6) causes this significantly higher value. They agree with Adensam et al. (2002) that GWP valuation highly influences results. To our knowledge, no analysis exists of how using a different valuation set affects the assessment and influences the search for more sustainable solutions. In addition, previous studies relate external costs mainly to construction costs, but do not align the life cycle phases considered for external costs to those considered for life cycle costs of the respective buildings.

Since construction costs or, in the context of sustainability, life cycle costs of buildings are an important criterion in the design process, calculating the monetary value of environmental impacts to find the most cost-efficient environmentally friendly solution fits well into the logic of design decisions. However, unlike in the Netherlands, where a monetary valuation system for buildings and civil engineering works has been established (Building Quality Foundation 2019), monetary valuation is not common practice in building LCA studies in Germany.

A monetary valuation approach in the construction industry has a two-fold advantage:

- Aggregation of a multitude of environmental indicators into one, easy-to-understand measure
- Comparability of alternative solutions in terms of economic and ecological aspects

2 Research goals

This study applies different EC models to the embedded environmental impacts of six German office buildings. As aggregating all environmental impacts to one value allows for direct comparison but at the same time loses the detailed information about single mid-points, we keep this information by showing the EC per mid-point-indicator. The results reveal the weights monetary valuation assigns to the different indicators and which environmental indicators are deemed the most significant for building construction. This offers the possibility of reevaluating the choice of currently used indicators in light of the particularities of the building industry, as it shows those impacts caused by construction that have a greater influence than others with respect to the chosen indicators.

Showing ranges of valuation makes it clear that EC assessment of buildings is quite dependent on the valuation methods applied and the resulting weighting of each impact category, while also indicating areas of the greatest potential for further research into the monetary valuation of environmental impacts of buildings. In addition, we investigate whether the valuation has an influence on the ranking of different building projects when comparing their environmental impacts.

Comparing environmental costs (i.e., external costs) to the life cycle costs (i.e., market prices) of the respective building shows how significant environmental pricing could be for various building parts and/or life cycle phases. It raises the question if and under which circumstances the internalization of external costs could lead to a more environmentally friendly solution by expressing its value in monetary terms and potentially tipping the business scale towards a solution with less environmental impact.

There is significant potential to improve the environmental quality of buildings if LCA is applied in the planning process. As LCA results are communicated to non-expert users in this process, it is vital for environmental issues to be as easily and unequivocally understood as possible to avoid their being partly or entirely ignored. This does not, of course, prevent more complex background information and methodological choices (e.g., relative weights of indicators) from being provided to expert users.

3 Methods

3.1 Life cycle assessment

Life cycle assessment in general consists of the four steps of goal and scope definition, inventory, impact assessment, and interpretation (DIN Deutsches Institut für Normung e.V. 2009). The goal of this study is the comparison of environmental impacts of a sample set of six different construction projects (see Section 3.4). The scope of the LCA study is aligned with the framework provided in the German sustainable building certification systems DGNB[1] and BNB.[2] These prescribe a study period of 50 years and reference service lives according to Bundesinstitut für Bau-, Stadt- und Raumforschung (BBSR) im Bundesamt für Bauwesen und Raumentwicklung (BBR) (2011). They also entail that inputs, outputs, and environmental impacts are calculated for life cycle phases A1-A3, B4, C3, and C4 (Fig. 2) according to DIN 15978 (DIN Deutsches Institut für Normung e.V. 2012). As phase D is only included in overall sums for the DGNB system, it is investigated separately. For this study, the embedded impacts of the buildings' construction are calculated excluding the buildings' operational phase (B6) and their mechanical, electrical, and plumbing (MEP) systems. The inventory includes all building parts for which the execution drawings provide information and excludes materials with a share of less than 1% of overall building mass.

Impact assessment includes the classification of emissions, i.e., the grouping of emissions according to their impact on the environment. The following step, characterization, entails assigning a factor to each substance in relation to the reference substance for the corresponding environmental impact. There are a number of methods for this characterization step, which are continuously further developed and refined. Ökobaudat, the database used for this study, prescribes a characterization method for each impact category included in the database by referencing DIN 15804 (DIN Deutsches Institut für Normung e.V. 2014).

This LCA study is concerned with environmental impacts and does not include social LCA, wider benefits, or other considerations of sustainability. Hence, environmental impact categories of DIN EN 15804 (DIN Deutsches Institut für Normung e.V. 2014) are evaluated with their corresponding characterization factors. LCAs are calculated on the basis of the German database Ökobaudat, version 2016-I, using the tool eLCA.[3] When data was not available in the Ökobaudat 2016-I, we draw on external data (e.g., data for carpets and glue were taken from Ökobaudat 2019-III). For purposes of the analysis, the structure of the cost groups of DIN 276 (Deutsches Institut für Normung e.V. 2008) is applied to the LCA results. We excluded the use of other databases, as this can skew results (Mahler and Schneider 2017).

In order to make the buildings, which are of different sizes, comparable, results are normalized to 1 m^2 usable floor area (UFA). The reference study period used for comparisons, including the building use phase, is 50 years. We worked with fixed scenarios and background data for both LCA and LCC to investigate the influence of monetary valuation on the overall ecological cost independently of LCA/LCC uncertainties.

3.2 Monetary valuation of environmental impacts

The recently established ISO 14008 (monetary valuation of environmental impacts and related environmental aspects) provides a framework for monetary valuation (International Organization for Standardization 2019) and shows that the method of monetary valuation of environmental impacts has attained recognition internationally.

Monetary valuation of environmental impacts determines currency values, sometimes denoted as the “shadow price” (Bickel and Friedrich 2005), of environmental damages (or benefits) caused by economic activities such as constructing, maintaining, and disassembling an office building, the subject of this study. Environmental impacts include impacts to ecosystems, human health, or human possessions. If damages caused and/or benefits accrued are not compensated for, they are known in environmental economics as externalities.

[2] Bewertungssystem Nachhaltiges Bauen (Evaluation System for Sustainable Building)

[3] www.bauteileditor.de

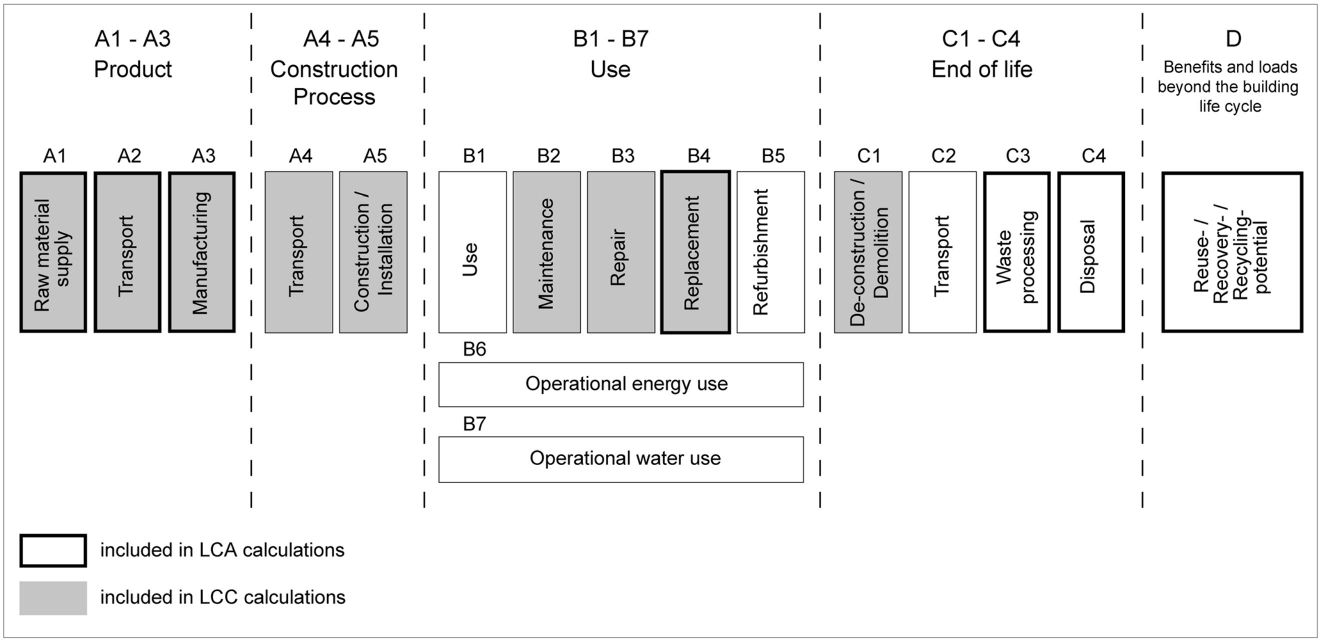

Fig. 2 Life cycle phases according to BS EN 15978 (British Standards Institution 2011), highlighting of phases considered in LCA/LCC calculations by authors

Although these externalities are not included in the (market) price of the product, several methods of quantifying them exist. Tekie and Lindblad (2013) provide a comprehensive overview. Not all monetary valuation methods are equally applicable to LCA studies (Pizzol et al. 2015), as LCA requires the valuation specifically of environmental impacts.

Valuation can be applied at different steps in the LCIA (Fig. 3). Some methods quantify directly the cost of emissions by assessing the external cost caused by the emission of single substances, e.g., the method used by the ExternE project (Bickel and Friedrich 2005). It is also possible to valuate impacts at mid-point, as done by Vogtländer (2017). Other methods provide values for end-point categories, e.g., Weidema (2009), Murakami et al. (2018), with or without disaggregation into corresponding mid-points. As Ökobaudat, the database used for this study, provides aggregated mid-point-indicators without full inventory data, we are limited to valuation systems providing values for mid-point indicators. There are overlaps with the systems that provide costs of emissions directly (Fig. 3: "unit conversion"), when the reference substance for a mid-point indicator is valuated, such as SO_2 (reference substance for acidification potential). Ideally, the characterization factors (CF) for the substances contributing to a mid-point indicator are identical with the ratio of the costs of emissions of the substances in question, or CF (substance A) = EC (substance A)/EC (reference substance). To give an example, the sum of the cost of SO_2 and NO_x emitted by a process should equal the cost of acidification potential measured in SO_2-equivalent. This only holds true if the characterization model and the unit conversion (nomenclature from ISO 14008 (International Organization for Standardization 2019)) are aligned.

We do not propose a new valuation set but rather vary the monetary values within the range provided by previous studies in order to analyze which weights result for the different impact categories. Additionally, large uncertainties are inherent within monetary valuation methods (Pizzol et al. 2015). This study gives an indication as to which differences in valuation play an important role for the resulting weighting in building LCA calculations. The studies and methods considered for this study are shown in Table 5.

A number of methods have been developed to assess external costs of environmental problems or qualities either by quantifying willingness to pay (WTP) or avoidance costs (Ahlroth et al. 2011). WTP can be revealed (e.g., damage costs), expressed (stated preference), imputed (e.g., substitution), or politically determined (e.g., in terms of taxes) (Ahlroth et al. 2011; Mishra 2006). Revealed WTP uses market prices as a basis. To determine expressed WTP, surveys need to be conducted in which individuals are asked to state their preferences, e.g., their WTP to avoid a marginal deterioration in environmental quality or quality of life. Imputed WTP methods investigate the prices an individual is willing to pay for the replacement of an environmental good or service or to avoid damages to it. Lastly, taxes can be used to estimate external costs, as they represent society's WTP to reach environmental targets (Finnveden et al. 2006). Avoidance, prevention, or abatement costs are calculated costs for measures that avoid emissions, e.g., the use of renewable energy sources in lieu of fossil energy sources in order to avoid CO_2 emissions. For avoidance costs, a target amount of emissions and either average or marginal costs to reach the set target need to be defined. There are differences between countries in how the economic value of damages and/or

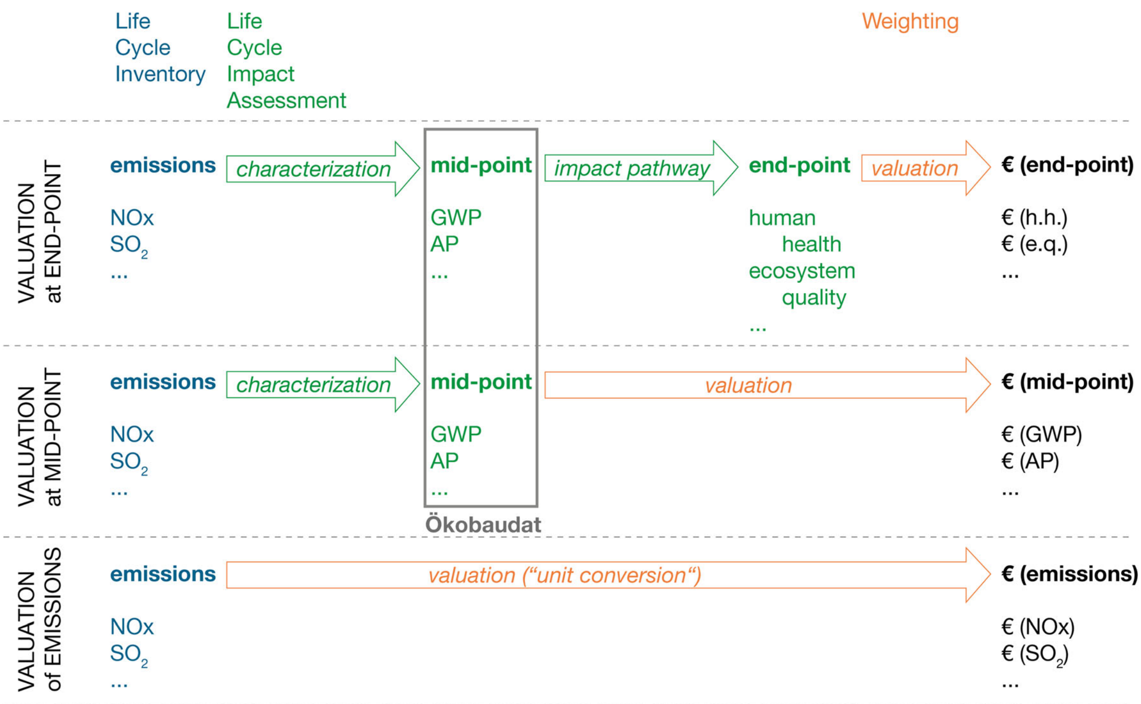

Fig. 3 Monetary valuation at different levels of aggregation in life cycle impact assessment (LCIA)

avoidance is assessed, i.e., equity weighting. Likewise, the question of whether and how future emissions should be discounted is answered differently. Hellweg et al. (2003) recommend that discounting should be subject to sensitivity analysis.

For this study, we consider environmental criteria, i.e., results from the LCIA. As energy is an input value into the system (Fig. 1) and therefore part of the life cycle inventory, it is not considered in our study. Adding a valuation for energy consumption double counts the valuation of the environmental impacts caused by energy consumption for the materials contained in the building. Comparing a monetary valuation of the mid-point impacts to a monetary valuation of the energy consumption related to the production and end of life of building materials is subject of further research. However, for the valuation of resources, we do consider the primary energy contained in a material (PENRM), as this energy is not consumed and hence has no environmental impact other than resource depletion.

3.2.1 Valuation of mid-point impacts

For this study, we draw a worst-case scenario for determining the maximum values of the environmental costs of the building: for this, we apply the greatest valuation found in literature for the mid-point indicator in question. As such, we determine if a high value for one impact category would lead to a more significant contribution to the overall external cost from the same. On the other end of the spectrum, we utilize the minimum values calculated in recent studies to define a best-case scenario, yielding a range of estimates. Table 1 shows the values used. If applicable, values were inflation adjusted per (OECD 2019) to the base year 2015 to match the LCC study. This method accepts the fact that the resulting minimum and maximum values mix different valuation models. The goal is to determine the effect of higher/lower valuation of environmental impacts in order to prioritize the reduction of uncertainty in valuation.

As the effects of global warming gain political importance, global warming potential (GWP) is by far the most discussed indicator in the recent literature. Twelve recent valuation models were considered for this study in conjunction with CO_2 pricing models currently on the market, such as the European Union Emissions Trading System (EU ETS), and implied pricing derived from NGOs offering CO_2 compensation for individual emissions, e.g., atmosfair (Germany) and MyClimate (Switzerland). The minimum valuation considered in this study[4] is the recent pricing for CO_2 compensation by atmosfair (atmosfair gGmbH 2019). This valuation is low because compensation projects seek out the most cost-efficient, "low-hanging fruits" for CO_2 prevention (Schultz et al. 2015). As, in nominal terms, this price has not changed from 2007 until now, we use this valuation for our study. In

[4] Even lower valuations, e.g., 0.0024€/kg CO_2-eq. by Friedrich et al. (2001), were not used here, as such low assessments largely seem to reflect the dates of these studies and appear outdated, as more recent updated (higher) values have become available for each system. Likewise, the recent CO_2-pricing plan issued by the German government BMU (2019) starting at 0.01€/kg CO_2 emissions for transport and space heating in 2020 was excluded as it does not apply to the embedded emissions in the building sector. Lastly, the EU ETS was excluded as prices for the certificates are highly volatile.

Table 1 Monetary valuation of mid-point indicators used in this study; global warming potential (GWP), ozone depletion potential (ODP), photochemical creation potential (POCP), acidification potential (AP), eutrophication potential (EP)

Environmental indicator	Unit	Min. valuation per unit	Source of min. valuation	Max. valuation per unit	Source of max. valuation
GWP	kg CO2-eq.	0.02 €	atmosfair gGmbH 2019	0.65 €	Matthey and Bünger (2019)
ODP	kg R11-eq.; kg FCKW-eq.; kg CFC11-eq.	0.00 €	Vogtländer 2016	30.00 €	the Bruyn et al. (2018)
POCP	kg C2H4 eq.	0.28 €	Adensam et al. 2002	10.02 €	Vogtländer (2016)
AP	kg SO2-eq.	1.77 €	Adensam et al. 2002	15.04 €	Bünger and Matthey (2018), Matthey and Bünger (2019)
EP	kg PO43-eq.	1.78 €	Adensam et al. 2002	18.52 €	Ahlroth (2009)

reality, the fact that the nominal price has not been adjusted implies that the inflation-adjusted price for the compensation of CO_2 emissions has decreased over the last 13 years. The highest valuation for the emission of greenhouse gases is taken from a recent report issued by the German Federal Environmental Agency (Matthey and Bünger 2019) and represents the (maximum) value recommended for sensitivity analyses with a base year of 2016. This valuation model does not discount future emissions and makes its evaluation based on a damage cost model.

Ozone depletion potential (ODP) is not intensely discussed in the recent literature, as the Montreal protocol has successfully regulated and reduced ozone-depleting substances. The eco-cost-value ratio (EVR) model by Vogtländer et al. (2001) valuates 1 kg CFC11-equiv. at zero eco-cost (Vogtländer 2016), as the substances causing ozone depletion are accounted for in the global warming prevention costs (Vogtländer 2017). This model determines marginal prevention costs, which do not allow for double counting and always use the higher valued prevention costs. The highest valuation is taken from the Bruyn et al. (2018), who valuate 1 kg CFC11-equiv. at 30.00 €. Their model uses ReCiPe characterization factors in conjunction with the NEEDs model. The costs in this method are prevention costs, defined as "the highest permissible cost level … for the government per unit of emission control" (the Bruyn et al. 2018). It is tailored to Dutch conditions and has to be modified for use in Germany, especially if ODP proves to be a relevant indicator considering the maximum values in this study. When using the maximum valuation for ODP and GWP in this study, there could be some double counting of the effects of emissions causing both ozone depletion and global warming. This has to be kept in mind when evaluating the results.

The remaining three categories differ from GWP and ODP insofar as they cause local rather than global effects. Therefore, resulting potential damages are more traceable but are also dependent on local circumstances, such as population density, the state of the local economy, or the type of adjacent land use.

The potential for summer smog or the formation of tropospheric ozone known as POCP (Photochemical Ozone Creation Potential) is considered to cause respiratory diseases and damage to agriculture and forests. The model of Adensam et al. (2002) values POCP lower than all other studies considered. Their valuation includes health costs caused by exposure to high ozone values. The authors state that additional potential damage to agricultural production and forestry is currently not quantifiable. Vogtländer (2016) values the marginal prevention costs of POCP significantly higher. As this contradicts the theory that prevention is more economical than repair, it seems to suggest that the damage costs might be valued too low or incompletely by the former model. Nevertheless, we used them as the lowest estimate for the EC of POCP.

For Acidification Potential (AP) and Eutrophication Potential (EP), the lowest values are again from Adensam et al. (2002). Both values represent the costs of damage. For AP, these include damage to human health, forests, and buildings. EP also causes health costs as it influences drinking water quality. Potential economic disadvantages to tourism caused by the eutrophication of water bodies were not quantified. The high estimate of the EC of AP is from Matthey and Bünger (2019). They valuate SO_2 emissions using the average damage costs of air pollution (emission) by unknown sources. Characterization was applied according to DIN 15804 (DIN Deutsches Institut für Normung e.V. 2014), as no conversion is available in the study. The upper limit for EP is taken from (Ahlroth 2009), representing damage cost estimates using individual willingness to pay and market prices.

The range of values of the environmental impacts is surprisingly large. All studies stress the high degree of variance in damage or prevention cost models. But, with the exception of Ahlroth (2009), who provides minimum and maximum values for abiotic resources, GWP, POCP and human toxicity, and some studies using minimum and maximum values for GHG emissions, none of the studies cited provides a range of values for all indicators.[5]

[5] The ranges provided by Ahlroth (2009) lie within the ranges considered in this study.

3.2.2 Valuation of resources

As the building sector consumes a large share of the world's resources (Klaassens 2014; Hegger et al. 2012), resource consumption is an indicator that should be considered when evaluating the ecological qualities of buildings. The question of whether and how to assess resources within the LCA framework is subject to controversy, and different methods have been developed for this assessment (Klinglmair et al. 2014; Giljum et al. 2011). As the extraction of natural resources affects the ecosystem and at the same time provides the basis for human economic activities, a complete valuation includes economic, socioeconomic, and ecological aspects. If resource depletion is evaluated from an ecological point of view, it relates to the overall (natural) availability of a given resource. Economic evaluation includes scarcity by relating the resource to the total stock available with current and/or future technologies of extraction. Socioeconomic aspects focus on a combination of a resource's scarcity and its importance to society to assess how critical it is.

Environmental impacts of resource extraction should be assessed in the impact assessment, whereas economic and social impacts should be modeled separately (Weidema et al. 2005). As life cycle phase A1 assesses environmental impacts from resource extraction itself, they are already included in the above life cycle assessment. Therefore, the valuation of resources in addition to the five impact categories described in Section 3.2.1 includes resource depletion as related to the natural availability of resources only. Van Oers and Guinée (2016) argue that ADPE/ADP_{elem} (abiotic depletion of elements) is therefore the only purely environmental indicator to be included in LCA calculations.

We calculate the ecological costs related to resource depletion separately from the costs of emissions to analyze the potential weight this indicator takes in building LCA evaluation. Ökobaudat (Bundesministerium des Innern, für Bau und Heimat (BMI) 2016) provides values for ADPF (abiotic depletion of fossil energy sources) in Megajoule (MJ) and ADP_{elem} in kg antimony-equivalents (Sb-eq.) as indicators of resource depletion. Both of these indicators are related to abiotic resources only and take into account the overall resource stock (DIN Deutsches Institut für Normung e.V. 2014). The underlying methodology and characterization was developed by the Institute of Environmental Sciences (CML) (van Oers et al. 2002). An updated indicator has been developed by van Oers and Guinée (2016), but is not included in Ökobaudat yet.

Little data is available regarding the valuation of resource depletion. The work-around suggested by Vogtländer (2016) is to value the non-renewable primary energy embedded in the material (PENRM) where detailed data about the resource depletion related to a particular material is not available. We use this as a test value to determine the relative weight of this indicator. Alternatively, evaluation of the depletion of antimony (Sb), the reference substance for ADP_{elem}, can be found in the EPS 2015d method (Steen and Palander 2016). This valuation (Table 2) is applied and results are compared.

3.3 Life cycle costs

Life cycle cost (LCC) calculations consider all costs related to the entire life cycle of the building, i.e., initial investment, costs during operation, and demolition costs. They are based on market prices and subject to price increases and discounting. For the life cycle of buildings, we use the life cycle phases according to DIN 15978 (DIN Deutsches Institut für Normung e.V. 2012) (Fig. 2) to align LCC with LCA calculations. Building life cycle costs (LCC) include construction, use and end of life—that is, life cycle phases A1-A3, B2-B4, and C1. Phases A4 and A5 are indirectly included in construction cost as they are generally included in the contractors' prices. For the same reason, they are not listed separately. Standardized data for C3, C4, and D is currently not available by product but is estimated on a building level. For the parameters discounting and price increase, the BNB certification system framework is used with an annual 2% price increase for building materials and services and a 1.5% discount rate for the evaluation of future investments. The base year used is 2015, the same as for the LCA calculations.

LCC reflect market prices for building products and services. In light of the presence of the European Emissions Trading System (EU ETS) for greenhouse gases, the question arises if some or all of the external costs of GHG emissions have already been internalized and are therefore included in the life cycle costs of buildings. Freeman et al. (1992) argue that tradable emission permits ensure the internalization of externalities under optimal trading rules (i.e., the marginal damage is equal for all sources). This means that the EU ETS would ensure that the external costs of GWP are already factored into the LCC. Under this circumstance, the price of the permit proves to be the marginal avoidance cost, as emitting facilities will avoid emissions if this can be achieved at a lower price than buying permits (Freeman et al. 1992). Although the first condition applies, as greenhouse gases cause the same amount of global warming regardless of their source, the EU ETS does not adhere to optimal trading rules. Firstly, in 2015, the base year of this study, the manufacturing industry received on average 66% of certificates free of charge

Table 2 Valuation of abiotic resource depletion *1 ELU (environmental load unit) = 1 €$_{2016}$

Indicator	Valuation	Source
PENRM	0.0167 €/MJ	Vogtländer (2016)
ADPelem	18,190 ELU/kg Sb*	Steen and Palander (2015)

(European Commission 2020). Secondly, this percentage varies significantly between industries, insofar as industries subject to an exposure to carbon leakage received emissions certificates equal to their predicted emissions free of charge. This applies to most of the industries manufacturing construction materials, e.g., the manufacturing of cement, steel, aluminum, and glass (European Commission 2014). Therefore, it is concluded for the purpose of this study that the external costs of direct GHG emissions caused by the manufacturing of construction materials have not been factored into the LCC. However, as power generators in most EU countries including Germany have to buy emission allowances, manufacturing processes buying electricity are subject to indirect price increase due to GHG emissions of electricity generation. Unfortunately, data to track the electricity used by the manufacturing of construction materials is not available. Therefore, we excluded this factor from this study also considering the low price of traded certificates in 2015 (between 7 € and 8 € per ton of CO_2-eq).

In order to normalize results and make them comparable to the LCA results, we used the usable floor area (UFA) as the functional equivalent, although LCC studies per the BNB framework use the gross floor area. The reference study period is the same as for the LCA calculation: 50 years. As the purpose of the LCC assessment in this study is to provide comparison values for the external costs, the same constant boundary conditions as for the LCA apply (e.g., products' standard service lives).

3.4 The case study projects

A set of six recent office buildings serves as a case study. They were built after 2009 and adhere to the German energy standard EnEV (Energieeinsparverordnung = energy saving ordinance) 2009. The construction type is similar, with concrete as the main structural material and either glazed curtain walls or facades made of concrete with exterior insulation and windows.

For all projects, LCA and LCC calculations were performed according to the framework described in Sections 3.1.and 3.3. Base data for the LCA and LCC calculations of projects A to E are taken from a previous study conducted by the authors and colleagues (Schneider-Marin et al. 2019). Figure 4 shows the sizes, number of floors, exterior wall, and roof types of the case study projects. In Table 3, general characteristics of the projects are listed.

Project F, the FTmehrHaus of Tausendpfund GmbH, was calculated additionally for this study providing different material options keeping everything else, e.g., energy standard, spatial organization, and geometry, the same between variations. The built structure uses three different exterior wall types for the three floors, as it serves as a test case for the owner, assessing thermal comfort in spaces with concrete, masonry, and sand-lime brick exterior walls. We varied insulation materials of each of these three wall types (variations F1 to F10) and also calculated 3 different subtypes of a wood frame construction for the exterior wall (variations F11 to F13). For comparison with projects A to E, an exterior glazed curtain wall was considered (variation F14). Greenhouse gas emissions emerged as a preponderant factor in the impact assessment (see Section 4). We therefore also calculated a wood structure (variation F15), adding up to a total of 15 construction material types.

4 Results

4.1 Environmental costs for five mid-point indicators

The LCA results of the case study project LCAs lay within a range considered acceptable by the DGNB system. For example, results for GWP for life cycle phases A1-A3, B4, C3, C4, and D lie between 8.32 kg CO_2/m^2 *a and 10.27 kg CO_2/m^2 *a, averaging 9.5 kg CO_2/m^2 *a. This is very close to the DGNB benchmark of 9.4 kg CO_2/m^2 *a (DGNB GmbH 2018).

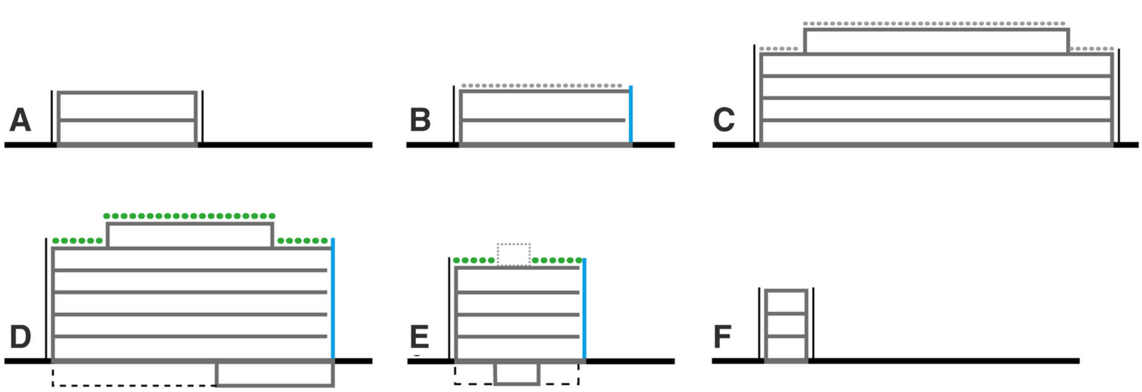

Fig. 4 Simplified representation of the case study projects showing size and number of floors

Table 3 Characteristics of the sample projects

Project	UFA (m^2)	Number of floors	Structure	Exterior walls	Window-to-wall ratio	Energy standard
A	2.512	2	Reinforced concrete	Reinforced concrete Exterior cladding: steel Windows/curtain wall: aluminum frame	0.41	EnEV 2014
B	3.039	2	Reinforced concrete	Reinforced concrete Exterior cladding: steel Windows: aluminum frame	0.37	EnEV 2014
C	15.006	5	Reinforced concrete	Reinforced concrete Ext. cladding: aluminum Windows: aluminum frame	0.27	EnEV 2014
D	13.685	6	Reinforced concrete	Reinforced concrete Ext. cladding: aluminum Windows/curtain wall: aluminum frame	0.25	EnEV 2009
E	4.504	4	Reinforced concrete	Reinforced concrete Ext. cladding: aluminum/concrete Windows/curtain wall: aluminum frame	0.28	EnEV 2014
F	1.060	3	Reinforced concrete	Reinf. concrete, Ext. cladding: EIFS (EPS) Windows: PVC frame	0.27	EnEV 2014

The EC for all sample projects were calculated according to the parameters described in Section 3. They are represented for three choices of life cycle phases: initial material use (product: A1 to A3), whole life cycle including use and end of life (A1 to A3 + B4 + C1 + C3), and additionally including end-of-life credits (A1 to A3 + B4 + C1 + C3 + D). The environmental impacts are converted into EC for the minimum and maximum EC values shown in Table 1. In general, most environmental impacts and therefore the larger share of EC occur in the product phases A1 to A3. This can be explained by the assumptions going into the calculations and by the data background: According to Ökobaudat, for all building materials, the product phase causes more environmental impacts than the end-of-life phase. Additionally, life cycle lengths of building materials vary between 15 and 50 years. With the bulk of the materials having a reference service life of 50 years or more, phase B4 causes fewer impacts than A1 to A3. The exchange and end-of-life phases add impact, whereas phase D contains some credits, i.e., overall impact decreases if phase D is considered.

4.1.1 Minimum valuation

Figure 5 shows that for the minimum valuation of all indicators, GWP dominates the overall EC for all projects. GWP contributes a minimum of 80% for phase A1-A3 (project E), 81% including end of life (projects D, E), and 81% including phase D (project E) to the overall EC. Its overall contribution can be up to 84% for phase A1-A3 (project F), 86% including end of life (project F), and 85% including phase D (project F).

AP is the second largest contributor, accounting for a minimum of 14% of the overall EC for phase A1-A3 (project F), 12% if end of life is included (project F), and 12% if phase D is included (project F). It can be responsible for up to 18% for phase A1-A3 (project E), 17% if end of life is included (project D), and 16% if phase D is included (project E).

It is interesting to see, however, that accounting for AP does not change the ranking of the projects significantly. Project F emits the least greenhouse gases and also shows the lowest EC whereas project D shows the highest values for both depending on the life cycle phases considered. For the projects in mid-range, A and E, accounting for AP has an influence, as their GWP values are very close. If life cycle phase D is considered, the ranking changes between projects C, E, and D, as their GWP values are again within a very close range or even equal. GWP, in other words, is the preponderant factor in determining the ranking of the case study buildings' environmental impact.

ODP does not contribute to the overall EC, as its EC are set to zero. POCP contributes between 0.2 and 0.8% and EP between 1.5 and 2.0% for all projects. This indicates that when EC is set to its minimum value found in the literature, the environmental impacts that should be considered first and foremost when constructing, maintaining, and demolishing buildings are GWP and AP, whereas ODP, POCP, and EP are almost negligible.

4.1.2 Maximum valuation

Assuming maximal EC estimations (Fig. 6) does not change this picture fundamentally, although GWP is even more

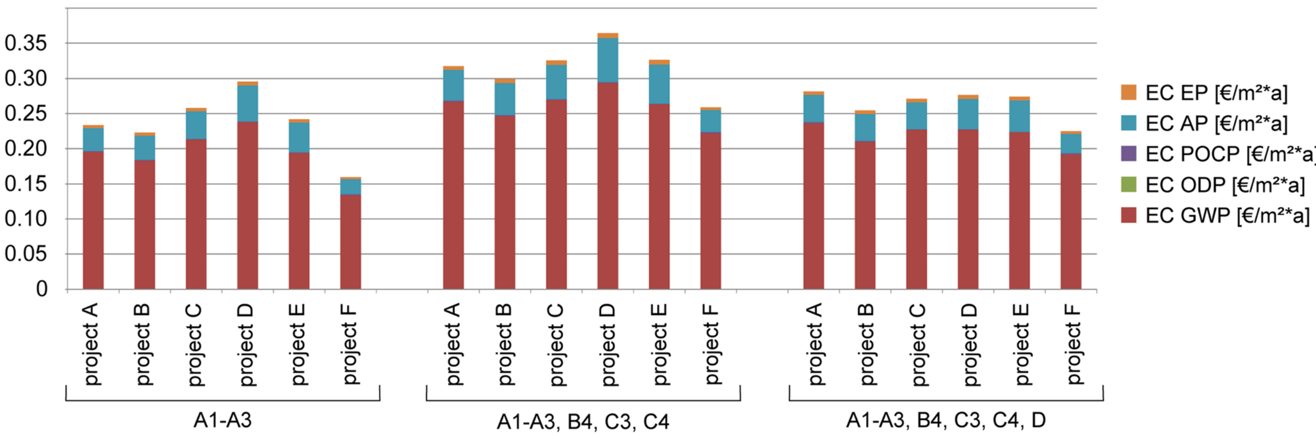

Fig. 5 Total minimum EC of the case study projects in € per m^2 UFA and year; subdivided in EC for eutrophication potential (EP), acidification potential (AP), photochemical creation potential (POCP), ozone depletion potential (ODP), and global warming potential (GWP); corresponding numbers are listed in Table 6

preponderant. GWP contributes between 92 and 94% to the overall EC, while AP is responsible for between 4 and 6%. Although the valuation of ODP, POCP, and EP is significantly higher than when minimal valuation is assumed (see Table 1), none of these indicators contributes more than 1.2%. This is interesting in light of the question if there might be some double counting of substances that contribute to both GWP and ODP, as we are using maximum valuation for both (see Section 3.2.1). The extremely low contribution of ODP, less than 0.000011%, indicates that, if there is some double counting, it is irrelevant to the overall result.

Using maximum values yields again almost the same ranking of the projects as ranking them according to GWP only, with the exception of projects that emit almost the same amount of GWP per m^2 and year. The only differences in ranking that result from including AP are between projects A and E for phase A1-A3, projects A and C if phase D is not considered, and, if phase D is considered, projects C, D, and E. None of the other indicators change any rankings.

Comparing minimum and maximum EC assessments, overall EC increase by a factor of 24.6 to 25.8 depending on the projects and the life cycle phases considered. About 93% of this increase is due to the 28-fold increase in the valuation of GWP. About 5% of the variance is due to the 8-fold increase in the valuation of AP. The large increases of the other indicators (e.g., EC_{max} (POCP) = 36 × EC_{min} (POCP); EC_{max} (EP) = 10 × EC_{min} (EP)) do not contribute significantly to the overall increase.

4.1.3 Influence of global warming potential

As the minimum and maximum valuation reveals the importance of GWP, we reduced GWP valuation to the point

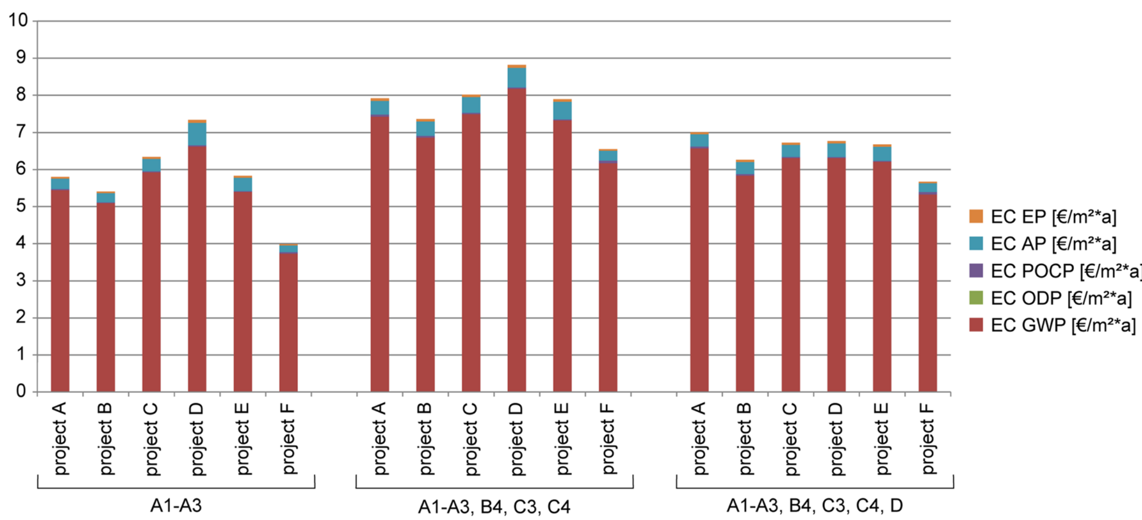

Fig. 6 Total maximum EC of the case study projects in € per m^2 UFA and year; subdivided in EC for eutrophication potential (EP), acidification potential (AP), photochemical creation potential (POCP), ozone depletion potential (ODP), and global warming potential (GWP); corresponding numbers are listed in Table 7

when its EC would cease to be as unequivocally important: GWP's contribution to overall EC is so preponderant that it only drops to about 50% when GWP's EC is set to 0.039 € per kg CO2-eq. while all other ECs are kept at their maximal assessments. For this specification, AP contributes 35 to 54%, EP between 6 and 8%, and POCP between 3 and 8%. ODP is still not relevant, with a contribution of 0.000041% or less to the overall EC. Alternatively, for AP to consistently account for 50% or more of the overall EC, GWP valuation would have to drop to 0.016 € per kg CO2-eq. The fact that GWP overwhelmingly determines the overall EC of all case study projects also broadly resonates with the fact that building construction contributes approximately 11% of global CO_2 emissions (International Energy Agency (IEA) 2018).

4.2 Taking resource depletion into account

In the previous section, Ökobaudat's five indicators directly related to environmental damage were considered. This section tackles the question of, in addition, taking resource depletion into account. Although only a few methods evaluating resource depletion at the mid-point level exist (Section 3.2.2.), an assessment on their basis nonetheless yields insights into the relative importance of this indicator while also highlighting differences in valuation.

Figure 7 shows a comparison between the direct valuation of ADP_{elem} and the work-around of valuating PENRM. In general, there are more significant differences between projects on the resource depletion count than on the other indicators considered in Section 4.1. However, the ranking of the projects is entirely dependent on the valuation method used, i.e., it changes almost completely depending on the method. Most notably, irrespective of the phases considered, Project F shows the highest EC using PENRM and the lowest EC of all projects using ADP_{elem} while Project E has the highest EC using ADP_{elem} and the lowest EC using PENRM, i.e., the points of the ranking are reversed. With the exception of project E, valuation of ADP_{elem} yields lower EC results than valuation of PENRM. Lastly, while employing ADP_{elem} substantially lowers the cost assessment of all other projects compared with their evaluation using PENRM, this change in method increases the cost assessment of project E.

We also see that, using the PENRM method, life cycle phases A1-A3 cease to be the dominant life cycle phases, with their maximum contribution to EC being 49.7% in project A. Phase D is insignificant, as there are no PENRM credits for any of the projects. This stems from the fact that the Ökobaudat 2016-I contains very few (a total of 21) building materials receiving a PENRM credit in phase D and none of them is used in any of the case study projects. When using ADP_{elem}, life cycle phases A1-A3 contribute between 52 and 82% of EC, and phase D provides a maximum credit of 6%.

In the context to the ECs calculated in Section 4.1, resource depletion EC is of significant magnitude. If the minimal valuation for all environmental impact indicators is used, EC of resource depletion adds at least 193% to the minimum EC (project D, LC phases A1-A3, APD_{elem}) and can add up to 2212% (project F, all LC phases, PENRM). Assuming maximal cost assessment, resource depletion adds between 7.4% (project F, all LC phases, APD_{elem}) and 74.6% to total EC (project F, LC phases A1-A3, C3, C4, D, PENRM).

For a more detailed analysis of the materials causing high values of the resource depletion indicators, we looked at the materials used in project E and project F. Project E stands out in its assessment under ADP_{elem} and project F in its assessment under PENRM. The former is also the only project for which ADP_{elem} yields higher EC than PENRM, the latter yields the highest values of all projects for PENRM.

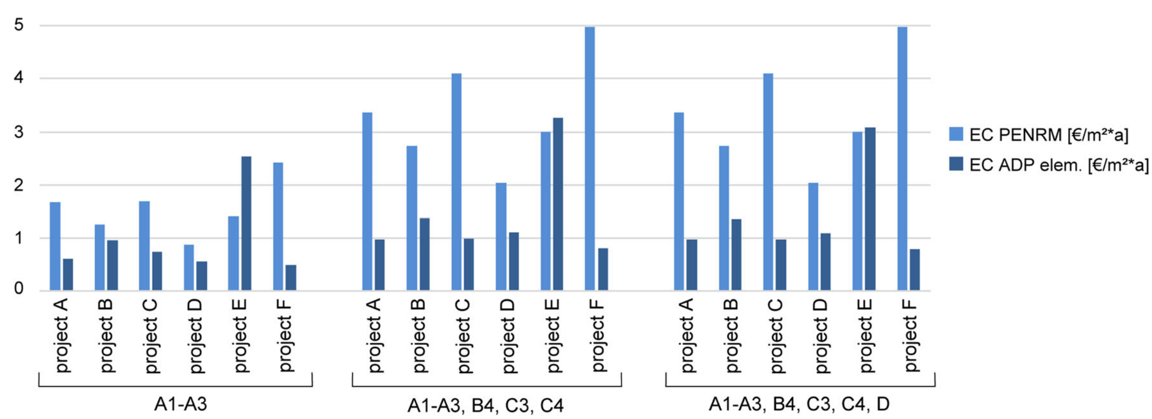

Fig. 7 EC of resource depletion of the case study projects in € per m^2 UFA and year; comparison between EC for non-renewable primary energy for material resources (PENRM) and abiotic depletion potential elements (ADPelem.); corresponding numbers are listed in Table 8

PENRM generates an extraordinarily high portion of project F's EC because of that project's exterior walls, namely, its EPS and XPS insulation and its PVC window frames. These elements have to be exchanged once during the reference study period, almost doubling the EC of the exterior walls. XPS and EPS are also applied in other projects causing high shares of PENRM, as do bituminous materials, but not to the extent as in project F. The high ADP_{elem} values for project E, by contrast, can be traced back almost exclusively to the stainless steel enclosure of some of the building's mechanical systems placed on the roof. The fact that this material is used in none of the other projects explains why project E yields an anomalous (because greater than under PENRM) EC when employing ADP_{elem}.

4.3 Relationship between environmental costs and life cycle costs

Fully internalizing EC into the life cycle costs of buildings allows for a better-informed cost-benefit analysis of more environmentally friendly, but potentially more costly, alternative building designs and construction methods. To see under which circumstances EC may influence such choices, we compared investment costs (costs for phases A1-A5) to EC for phases A1-A3, as well as life cycle costs (LCC) for all phases considered in standard LCC calculations to life cycle EC. Phase D is excluded from this comparison, as no cost credit data exist for benefits and loads outside of the system boundary. As phases B2 (maintenance) and B3 (repair) are not accounted for in the LCA calculations (Fig. 2), we show the costs of these phases separately from other phases.

Figure 8 illustrates that EC derived from minimal cost assumptions account for a mere 1.04 to 1.46% of building construction cost for phases A1-A3 and even less (0.66 to 0.80%) if life cycle costs and the full life cycle is considered (phases A to C). EC using maximal cost assumptions, however, is equal to between 26 and 37% of construction costs, 16 to 20% of total LCC, and 23 to 34% to LCC disregarding phases B2 and B3. The difference between EC and LCC increases for the full life cycle, as the use phase (not including energy use for building operation) adds more costs than environmental impacts.

It is evident that EC and LCC are not inversely correlated, i.e., projects with lower EC are not necessarily more expensive. On the contrary, Project F, for instance, shows both low EC for phases A1-A3 and low construction costs. For the full life cycle (excluding B2 and B3), project F has the second-lowest LCC and the lowest EC. On the other end, project E, with the highest construction and life cycle costs, shows a mid-range EC.

4.4 Minimizing environmental costs

Different variations of project F (Table 4) were investigated in order to minimize its EC. As GWP appears to be the preponderant indicator, variation F15 replaces the reinforced concrete structure with a wood structure in order to realize the large GWP dividend implied by this change. In particular, Ökobaudat attributes a GWP credit to wood in phase A1-A3 for carbon storage, allowing project F15 to show negative EC for these phases.

F15 contains approximately 225 metric tons of wood (and equal amounts of concrete for the base plate), compared with approximately 1412 tons of concrete in versions F1-F3, not considering reinforcement. (These variations contain the highest amount of concrete, as their exterior walls are made of this material.) This choice comes without clear trade-offs in terms of the other, non-GWP,

Fig. 8 Comparison of EC and LCC of the sample projects in € per m^2 UFA and year; LCC are subdivided into (partial life cycle) costs for maintenance (B2) and repair (B3) and (partial) life cycle costs A1-A3, B4, and C1; corresponding numbers are listed in Table 9

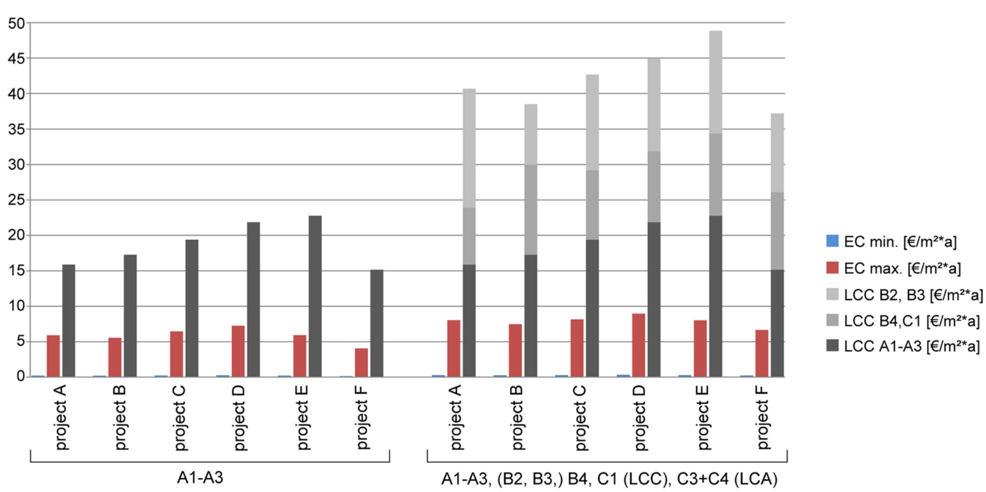

Table 4 Characteristics of variations on project F

Variation	Structure	Exterior walls	Window frames
F1 (project F)	Reinforced concrete	Reinf. concrete + EIFS (185 mm EPS)	PVC
F2	Reinforced concrete	Reinf. concrete + EIFS (185 mm mineral wool)	PVC
F3	Reinforced concrete	Reinf. concrete + EIFS (185 mm EPS, lightweight plaster)	PVC
F4	Reinforced concrete	Masonry + EIFS (65 mm EPS)	PVC
F5	Reinforced concrete	Masonry + EIFS (65 mm mineral wool)	PVC
F6	Reinforced concrete	Masonry + EIFS (65 mm EPS, lightweight plaster)	PVC
F7	Reinforced concrete	Masonry + EIFS (65 mm wood fiber)	PVC
F8	Reinforced concrete	Sand-lime brick + EIFS (190 mm EPS)	PVC
F9	Reinforced concrete	Sand-lime brick + EIFS (190 mm mineral wool)	PVC
F10	Reinforced concrete	Sand-lime brick + EIFS (190 mm EPS, lightweight plaster)	PVC
F11	Reinforced concrete	Wood frame + fiber cement siding	PVC
F12	Reinforced concrete	Wood frame + EIFS (wood fiber)	PVC
F13	Reinforced concrete	Wood frame + ext. plaster (ventilated)	PVC
F14	Reinforced concrete	Aluminum/glass curtain wall	N/A
F15	Wood; Base plate: concrete	Wood frame + ext. plaster (ventilated)	Wood

indicators (Fig. 9). Looking at the underlying indicators, F15 ranks are lowest for both GWP and POCP. While it shows by far the highest values for ODP (7 to 12 times the lowest values) and the second highest values for EP (F14 yields the highest value), these impacts are almost negligible in terms of the overall EC. As a result, F15 emerges as the lowest overall EC option for phases A1 to A3 and full life cycle (including D). Other variations with wood exterior walls (F11 to F13) also substantially reduce EC during these phases.

As wood receives GWP credits for A1-A3, emissions from the end-of life scenario of combustion (for energy generation) are accounted for in phase C3. Therefore, the EC of project F15 are closer to other variants if the full life cycle without phase D taken into account. It is interesting to see that variant F14 (glazed curtain wall) shows lower EC than the variants with wood exterior walls F11 to F13 for the full life cycle without D. This is due to the end-of-life scenario (recycling) of the curtain wall system.

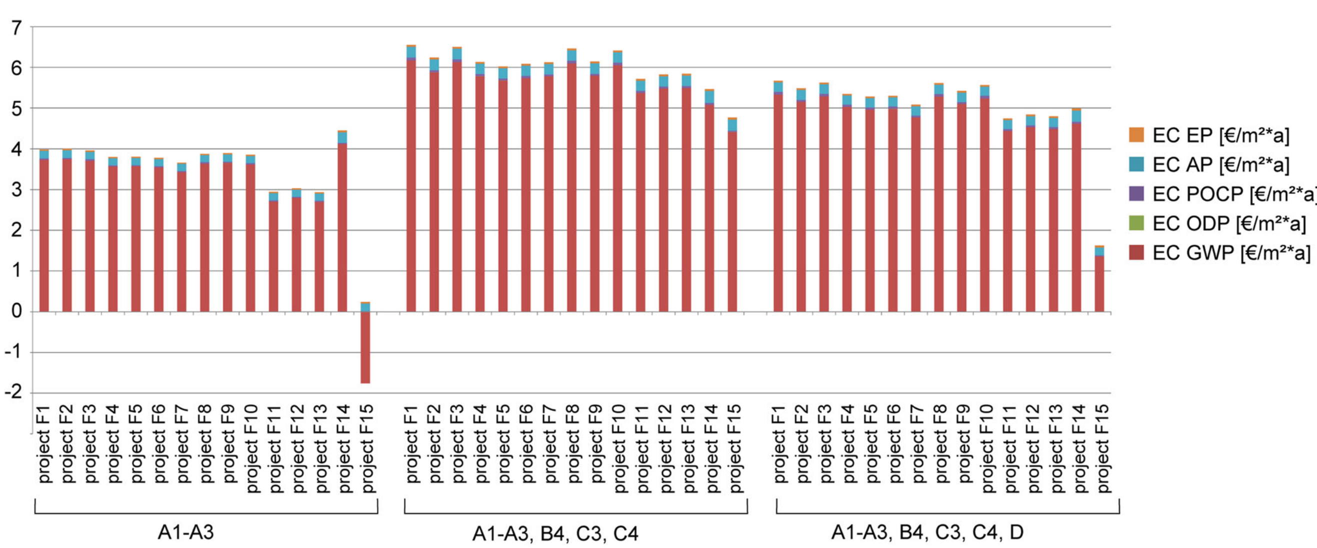

Fig. 9 Total maximum EC in € per m^2 and year of different variations of project F; subdivided in EC for eutrophication potential (EP), acidification potential (AP), photochemical creation potential (POCP), ozone depletion potential (ODP), and global warming potential (GWP); corresponding numbers are listed in Table 10

The life cycle phases considered impact EC assessments heavily. Generally, wood and other renewable materials are at a disadvantage if phase D is not taken into account. These materials are in contrast at an advantage if only the production phases A1-A3 are considered. This might change drastically if other databases than Ökobaudat are used, as most databases do not give carbon storage credits to renewable materials. The choice of exterior wall materials influences overall results, but only a change in the structural material makes a significant difference in EC.

5 Discussion and conclusions

This study shows that expressing environmental impacts in terms of monetary units has potential for application in the building industry. It offers the opportunity to condense several environmental indicators to one value and hence can help planners and consultants to communicate the results of their investigations of the ecological quality of buildings to clients and stakeholders. Monetary units are easily understood by a layperson and can therefore facilitate including environmental aspects into decision processes. Alternative solutions become comparable in terms of ecological aspects which can also be used in cost-benefit analyses.

Comparing valuation from differing sources and contexts reveals the broad range of actual values assigned to environmental impacts. This cannot be traced back to one particular valuation method, such as damage costs or marginal prevention costs, but appears to be inherent in monetary valuation, as the monetary values of environmental damages and benefits are incomplete and subject to uncertainties. This implies that valuation methods still have gaps and agreed-upon values for emissions are missing. For our study, we used maximum and minimum valuation found in literature in order to determine the resulting range in ecological cost (EC) of buildings and the resulting contribution of each environmental indicator, i.e., the weighting that results from monetary valuation.

The case study of six different construction projects reveals that the contribution of single indicators towards the overall ecological cost (EC) stays consistent, independently of the order of magnitude of the cost assessment. However, the wide variation in terms of assigning monetary values does pose significant challenges to a consistent and generally agreed-upon method for communicating or internalizing EC. The cost values for single mid-point indicators in recent studies differ by a factor of up to thirty-six (photochemical creation potential, POCP), or even range from zero to 30 € (ozone depletion potential, ODP). Despite this broad range, of the environmental indicators considered, GWP (attributed to the use of fossil fuels and fossil resources and cement production) has the greatest effect (at least 80%) on the overall EC of the buildings considered in the case study. In this, we agree with the previous studies conducted by Adensam et al. (2002) and Ulmer et al. (2010). Acidification potential (AP) with a contribution between 4 and 17% can tip the scale towards one project over another only if GWP results for the projects to be compared are in close proximity. Otherwise, a ranking of the projects regarding their environmental evaluation according to EC is identical with a ranking according to GWP. Hence, considering the ranking of projects according to only GWP provides a good approximation for the environmental quality according to the five commonly used indicators (eutrophication potential (EP), acidification potential (AP), photochemical creation potential (POCP), ozone depletion potential (ODP), and global warming potential (GWP)). Acidification potential (AP) can provide additional information if GWP values are similar between projects. For the development of a model for the valuation of environmental costs for embedded impacts for the building industry, GWP and AP are clearly the indicators that should be prioritized.

To put the order of magnitude of potential EC into perspective and evaluate their possible integration into a decision process based on economic factors, we juxtaposed the EC to the LCC of the corresponding life cycle phases. This shows that, even if the highest value recommended for sensitivity analyses is used, internalizing EC into building costs adds no more than 34% to construction costs. Hence, it is questionable if a low valuation of EC (in fact, tantamount to a low valuation of GWP) will be useful as a basis for decisions in the building industry. In such a case, if the valuation of GWP is at the lower end, the overall EC are low in comparison to LCC: around 1%. For a decision process, this means that the difference in EC between alternative project options could be insignificant compared with a difference in construction and/or life cycle costs. If valuation is at the higher end, integrating EC into project comparison can make a difference. All in all, valuation of environmental costs should be used with caution to avoid the false impression that paying a small additional sum solves all environmental problems related to constructing, using and demolishing buildings: other, unaccounted for externalities exist, and not all of them may be measurable in terms of monetary value. One of these potential factors is toxicity, which could not be considered in this study, as the database used (Ökobaudat) does not provide data for this indicator.

The consideration of resource depletion in the case study suggests that this indicator should be taken into account in building EC assessments as it contributes significantly to overall EC. However, only very few methods to assess resource depletion are available. The two methods for doing so that are considered here yield contradictory results. For the valuation of non-renewable primary energy embedded in the material (PENRM), the use of plastics is the most decisive factor. In case of the valuation of abiotic depletion potential (elements) (ADP_{elem}), metals contribute the highest share. This results in the ranking of the case study projects drastically changing depending on the base value (energy input or mid-point) employed. Unlike the valuation of other environmental indicators, the valuation of ADP_{elem} can be traced back to one single material used. Notably, this material (stainless steel) could be fairly easily be substituted to lower the valuation for resource depletion. This also points to the fact that excluding materials with a small contribution to the overall mass of the building, e.g., attachment screws, could potentially influence the overall resource consumption disproportionally and might have to be reconsidered. Overall, the fact that the valuation of buildings regarding resource depletion needs to be further investigated is in line with the building industry's high relevance for the consumption of the world's resources.

The evaluation of different variations in the choice of specific materials and components of one sample project indicates the possibility of lowering EC by using wood-based construction materials with low GWP. The dominance of GWP is responsible for the overall EC shrinking without significant trade-offs towards other indicators when a low GWP material is used. But, notably, the end-of-life phases impact the results significantly, as the assessment of different variations of this project change drastically and non-uniformly depending on whether or not these phases are taken into account. This is a direct effect of the accounting for carbon storage in Ökobaudat, providing GWP credits for the product phase, GWP for emissions from combustion in phase C3, and again GWP credits for the replacement of energy from fossil sources in phase D. Further research is needed to compare the results using other databases such as ecoinvent,[6] which do not give GWP credits for the carbon storage of wood.

Beyond application of EC in decision processes the question remains if and how EC might be internalized. EC for the product phase (A1-A3) would appear in product pricing, due to environmental taxation or emissions trading. End-of-life costs could only be factored into product prices if producer responsibility can be guaranteed. EC for other life cycle phases (with the exception of the product part of B4) would have to be internalized at the building level.

This study is limited to embedded environmental impacts and hence excludes energy use during building operation. A separate study of the EC of building operation is needed as previous investigations (Schneider-Marin et al. 2019) show that internalizing EC into the cost of building operation increases operational costs by a significantly higher percentage than internalizing embedded EC into LCC without phase B6. However, if building operation is considered, EC based on the valuation of mid-points-indicators needs to be compared in detail to available EC based on energy sources, i.e., fuel types or renewable sources and electricity mix. In order to gain a complete picture about interdependencies between emissions and energy generation and distribution systems, building services (cost group 400) should also be included.

In this study, office buildings and the materials used in these buildings are considered. Residential or industrial buildings might show different results, but it is unlikely that the overall weighting of indicators would change dramatically, as the bulk of the materials used are comparable. In this context, too, resource depletion has to be carefully considered as single materials can highly influence results.

We conclude that monetary valuation of environmental impacts is a valuable tool for comparisons of different buildings and design options, as they enable LCA practitioners to aggregate results to a single value. Of the indicators considered, GWP proves to have the highest influence on the overall EC of the case study buildings. Therefore, future studies should always consider a range of GWP pricing rather than a single value. The valuation of resource depletion is potentially as influential as GWP valuation and hence requires further research, as to date only few valuation methods are available. The ratio of EC to life cycle costs varies following the magnitude of GWP pricing to such an extent that using EC in project comparison in direct relation to LCC only has a significant influence if GWP pricing is at the higher end of the spectrum.

Acknowledgments Open Access funding provided by Projekt DEAL. The authors would like to thank their colleagues at the Institute of Energy Efficient and Sustainable Design and Building, especially Hannes Harter, Christina Meier-Dotzler, and Christine Röger and their project partners at ATPsustain Munich, Jens Glögger and Klara Meier, for their work on the Design2Eco project, their continuous support, and their availability for discussions. Furthermore, we thank Ferdinand Tausendpfund GmbH & Co. KG for providing their office building as a sample project. For their scientific input and valuable feedback, we sincerely thank Dr. Joost Vogtlander and Dr. Leander Schneider. We also thank our anonymous reviewers for their thoughtful comments and efforts towards improving our manuscript.

Funding information Funding for the Design2Eco project and thereby for the LCA and LCC calculations of projects A-E was received from Bundesministerium des Innern, für Bau und Heimat, Germany, under grant number SWD10.08.18.7.-16.60, and from ATP Planungs- und Beteiligungs- AG, BayWa AG, and Stiftung Bayerisches Baugewerbe.

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Appendix 1. External cost studies

Table 5 Monetary valuation models considered for this study

Method	Year	Emissions/immissions	Mid-points/end-points	Monetary valuation method	Purpose
ExternE (Bickel and Friedrich 2005)	1995, 1999, 2005	PM_{10}, $PM_{2,5}$, SO_2, NO_x, NMVOC, NH_3, CO_2, CH_4, N_2O, mercury, noise	Global warming, human health (morbidity/mortality), building material, ecosystems, crops, amenity losses, land use change	Impact Pathway Approach, WTP to avoid individual welfare loss	Policy making
NewExt (Rabl et al. 2004)	2004	Nitrates, sulfates, PM_{10}, SO_2, arsenic, cadmium, chromium, lead, nickel, formaldehyde	Health impacts, global warming, damage to buildings and materials, acidification, eutrophication	Impact Pathway Approach; WTP for mortality risk reductions; revealed preferences in political negotiations and public referenda	Improve ExternE assessment system; Policy making
NEEDS (Preiss et al. 2008)	2009	aNH_4, aNO_3, DEP_OXN, DDEP_RDN, DDEP_SOX, NOx, pNO_3, SIA, SO_4, SOMO35, tNO3, WDEP_OXN, WDEP_RDN, WDEP_So_x, PPM_{25}, PPM_{co}, heavy metals, formaldehyde, dioxins, and others	Land use changes, acidification, eutrophication, visual intrusion, climate change, human health impact	Impact Pathway Approach; (based on ExternE, NewExt)	Policy making: future electricity supply
CASES (Cost Assessment for External Energy Systems) (Markandya 2008)	2008	CO_2, NH_3, NMVOC, NO_X, PPM_{co}, PPM_{25}, SO_2, Cd, As, Ni, Pb, Hg, Cr, CR-VI, Formaldehyde, Dioxin, and others	Environmental damages (human health, environment, crops), damage to materials, loss of biodiversity, climate change	Impact Pathway Approach (based on ExternE)	Evaluate policy options
LIME (life cycle impact assessment method based on end-point modeling	Lime-1: 2000 Lime-2: 2006 Lime-3: 2016	CO_2, CH_4, N2O, HFCs, PFCs, SF_6, CFCs Halons, CCI4, 111-TCE, HCFCs, CH_3Br, NMVOCs, NO_X, SO_2, Arsenic, Benzene, and others	Human health, social assets, biodiversity, primary production, GWP, ODP, POCP, urban air pollution, chemical substances, eco-toxicity, land use, resource consumption, waste, land use	Conjoint analysis, WTP	Database for industry in Japan, decision--making; weighting factors for G20 countries
Virtual Pollution Prevention costs 99 (eco-cost) (Vogtländer 2016)	2000, up-dated in 2007, 2012 to pres-ent		Human health, eco-toxicity, resource scarcity, carbon footprint/GWP, ODP, POCP, EP, AP, Toxicity	Marginal abatement costs	Application by designers and engineers for decision--making
Ecovalue 08/ Ecovalue12 (Ahlroth and Finnveden 2011, Finnveden et al. 2013)	2009, 2012		GWP, POCP; AP, EP, Humantox, Marinetox, ADP, Particles	Damage cost: WTP estimates/resource depletion: market prices	Weighting
Environmental Priority Strategies (EPS) (Steen and Palander 2016)	1989, 1994, 1996, 2000, 2015		Human health, production capacity of ecosystems, abiotic stock resources	WTP for damage avoidance, quantification of the change in value for end-point indicators due to emissions	Weighting, decision--making
Stepwise 2006 (Weidema 2009)	2009	CO_2, CO, NO_x, PM_{10}, $PM_{2.5}$, SO_2, VOC	Human health, ecosytems, natural resource use, eco-toxicity, human toxicity, GWP, ODP, POCP; AP, EP (aquatic, terrestrial), and others	Budget Constraint Method	
Handbook on the external costs of transport	2008, 2014, 2019 (base		Accidents, air pollution, climate change, noise, congestion, well-to-tank emissions, habitat damage, soil and water pollution, and others		Policy making; internalizing social costs

Table 5 (continued)

Method	Year	Emissions/immissions	Mid-points/end-points	Monetary valuation method	Purpose
	year 2016)				
UBA Methodenkonvent-ion (German Environment Agency Methodological convention) (Bünger and Matthey 2018)	2018	PM2.5, PMcoarse, PM10, NOX, SO2, NMVOC, NH3	GWP	Equity Weighting, varying scenarios for discounting	Policy making, internalizing external costs
Externe Kosten im Hochbau (external costs in building construction) (Adensam et al. 2002)	2002		GWP, ODP, AP, EP, POCP	Damage costs (GWP), avoidance costs	Weighting

Appendix 2. Case study results

Table 6 Minimum EC of the case study projects in € per m^2 UFA and year

		EC GWP (€/m²*a)	EC ODP (€/m²*a)	EC POCP (€/m²*a)	EC AP (€/m²*a)	EC EP (€/m²*a)	EC PENRM (€/m²*a)	EC ADP elem. (€/m²*a)	TOTAL EC (no RD) (€/m²*a)
A1-A3	project A	0.195606919	0	0.000932385	0.032815977	0.004009904	1.642078884	0.616715971	0.233365184
	project B	0.18313109	0	0.000880171	0.034571644	0.004273385	1.237144934	0.964171437	0.22285629
	project C	0.213050631	0	0.000692349	0.039532373	0.004661715	1.666446795	0.753739856	0.257937068
	project D	0.237997601	0	0.000716518	0.051494105	0.005293717	0.868116731	0.565758828	0.29550194
	project E	0.193922637	0	0.000586688	0.04274227	0.004570102	1.388988864	2.537043469	0.241821698
	project F	0.134060623	0	0.001064958	0.021695103	0.002808995	2.379751839	0.494482861	0.159629679
A-C	project A	0.267098845	0	0.00152349	0.043784181	0.005276027	3.303665353	0.979454268	0.317682543
	project B	0.246655057	0	0.001367528	0.045511065	0.005846444	2.69231178	1.373062777	0.299380094
	project C	0.269438845	0	0.000995906	0.048867215	0.006066463	4.02858496	0.989891142	0.325368429
	project D	0.29382691	0	0.000941994	0.062571863	0.006958049	2.006960504	1.106903876	0.364298817
	project E	0.263383825	0	0.000849893	0.055711638	0.00627434	2.949461107	3.271993124	0.326219695
	project F	0.221835667	0	0.001944721	0.031269264	0.004014567	4.882947689	0.805222449	0.259064219
A-C-D	project A	0.236247235	0	0.001438082	0.039023579	0.00475486	3.303665353	0.973935095	0.281463756
	project B	0.209746033	0	0.001228539	0.038306128	0.005170153	2.69231178	1.368275712	0.254450853
	project C	0.226848994	0	0.000873651	0.038091328	0.005233667	4.02858496	0.977656763	0.271047641
	project D	0.226851236	0	0.000728868	0.04330286	0.005582914	2.006960504	1.090033482	0.276465878
	project E	0.223237331	0	0.000714006	0.044812409	0.00548121	2.949461107	3.084380001	0.274244955
	project F	0.191474394	0	0.001892622	0.02779115	0.003578641	4.882947689	0.792618928	0.224736806

Table 7 Maximum EC of the case studies in € per m^2 UFA and year

		EC GWP (€/m²*a)	EC ODP (€/m²*a)	EC POCP (€/m²*a)	EC AP (€/m²*a)	EC EP (€/m²*a)	EC PENRM (€/m²*a)	EC ADP elem. (€/m²*a)	TOTAL EC (no RD) (€/m²*a)	factor EC min.
A1-A3	project A	5.54503092	3.94605E-07	0.033727412	0.278843101	0.041721022	1.642078884	0.616715971	5.89932285	25
	project B	5.191368298	6.23783E-07	0.031838671	0.293761315	0.044462408	1.237144934	0.964171437	5.561431315	25
	project C	6.039522247	6.38666E-07	0.025044528	0.335913497	0.048502783	1.666446795	0.753739856	6.448983693	25
	project D	6.746714588	4.92016E-07	0.025918806	0.437554429	0.055078449	0.868116731	0.565758828	7.265266764	25
	project E	5.4972852	4.75413E-07	0.02122245	0.363188558	0.047549598	1.388988864	2.537043469	5.929246281	25
	project F	3.800327227	5.04344E-07	0.038523032	0.184347086	0.029226173	2.379751839	0.494482861	4.052424022	25
A-C	project A	7.571671603	4.98011E-07	0.055109642	0.372041855	0.054894396	3.303665353	0.979454268	8.053717993	25
	project B	6.99213465	7.8846E-07	0.049467976	0.386715489	0.060829296	2.69231178	1.373062777	7.4891482	25
	project C	7.638005528	8.96975E-07	0.036025187	0.415233284	0.063118475	4.02858496	0.989891142	8.152383372	25
	project D	8.329354152	6.72988E-07	0.034075026	0.531684078	0.072394984	2.006960504	1.106903876	8.967508914	25
	project E	7.466358854	6.05169E-07	0.030743413	0.473391543	0.065281338	2.949461107	3.271993124	8.035775754	25
	project F	6.288558899	6.07282E-07	0.070346954	0.26570041	0.041769543	4.882947689	0.805222449	6.666376413	26
A-C-D	project A	6.697095526	3.15802E-07	0.052020168	0.331590186	0.049471914	3.303665353	0.973935095	7.13017811	25
	project B	5.945844061	6.04712E-07	0.044440283	0.325493879	0.053792831	2.69231178	1.368275712	6.369571659	25
	project C	6.43067584	8.22749E-07	0.031602842	0.323668683	0.05445366	4.02858496	0.977656763	6.840401847	25
	project D	6.430739387	4.27801E-07	0.026365551	0.367951987	0.058087393	2.006960504	1.090033482	6.883144745	25
	project E	6.328293027	3.96736E-07	0.025827948	0.380778885	0.057029214	2.949461107	3.084380001	6.791929471	25
	project F	5.427882811	3.84347E-07	0.068462347	0.23614627	0.037233945	4.882947689	0.792618928	5.769725757	26

Table 8 EC of resource depletion

		EC PENRM(€/m²*a)	EC ADP elem.(€/m²*a)
A1-A3	Project A	1.64207888	0.61671597
	Project B	1.23714493	0.96417144
	Project C	1.66644679	0.75373986
	Project D	0.86811673	0.56575883
	Project E	1.38898886	2.53704347
	Project F	2.37975184	0.49448286
A-C	Project A	3.30366535	0.97945427
	Project B	2.69231178	1.37306278
	Project C	4.02858496	0.98989114
	Project D	2.0069605	1.10690388
	Project E	2.94946111	3.27199312
	Project F	4.88294769	0.80522245
A-C-D	Project A	3.30366535	0.97393509
	Project B	2.69231178	1.36827571
	Project C	4.02858496	0.97765676
	Project D	2.0069605	1.09003348
	Project E	2.94946111	3.08438
	Project F	4.88294769	0.79261893

Table 9 Comparison of EC and LCC of the sample projects

		EC min. (€/m^2*a)	EC max. (€/m^2*a)	LCC (€/m^2*a)	EC min/LCC (%)	EC max/LCC (%)
A1-A3	Project A	0.23	5.90	15.88	1.47	37
	Project B	0.22	5.56	17.24	1.29	32
	Project C	0.26	6.45	19.36	1.33	33
	Project D	0.30	7.27	21.85	1.35	33
	Project E	0.24	5.93	22.75	1.06	26
	Project F	0.16	4.05	15.18	1.05	27
A1-A3, B4, C1, C3, C4	Project A	0.32	8.05	40.65	0.78	20
	Project B	0.30	7.49	38.52	0.78	19
	Project C	0.33	8.15	42.67	0.76	19
	Project D	0.36	8.97	44.88	0.81	20
	Project E	0.33	8.04	48.84	0.67	16
	Project F	0.26	6.67	37.22	0.70	18
A1-A3, B2, B3, B4, C1, C3, C4	Project A	0.32	8.05	23.87	1.33	34
	Project B	0.30	7.49	29.95	1.00	25
	Project C	0.33	8.15	29.19	1.11	28
	Project D	0.36	8.97	31.89	1.14	28
	Project E	0.33	8.04	34.37	0.95	23
	Project F	0.26	6.67	26.10	0.99	26

Table 10 Maximum EC in € per m^2 and year of different variations of project F

		EC GWP (€/m²*a)	EC ODP (€/m²*a)	EC POCP (€/m²*a)	EC AP (€/m²*a)	EC EP (€/m²*a)	TOTAL EC (no RD) (€/m²*a)
A1-A3	project F1	3.80	0.00	0.04	0.18	0.03	4.052424022
	project F2	3.82	0.00	0.03	0.19	0.03	4.071260832
	project F3	3.78	0.00	0.04	0.18	0.03	4.028932364
	project F4	3.63	0.00	0.03	0.17	0.03	3.867838856
	project F5	3.64	0.00	0.03	0.18	0.03	3.874457194
	project F6	3.61	0.00	0.03	0.17	0.03	3.844347198
	project F7	3.49	0.00	0.03	0.18	0.03	3.725837893
	project F8	3.71	0.00	0.04	0.17	0.03	3.944608877
	project F9	3.73	0.00	0.03	0.18	0.03	3.96395479
	project F10	3.69	0.00	0.04	0.17	0.03	3.921117219
	project F11	2.76	0.00	0.03	0.18	0.03	2.993140568
	project F12	2.85	0.00	0.03	0.17	0.03	3.079664056
	project F13	2.75	0.00	0.03	0.18	0.03	2.984590514
	project F14	4.20	0.00	0.03	0.26	0.04	4.526435149
	project F15	-1.80	0.00	0.02	0.18	0.04	-1.55437006
A-C	project F1	6.29	0.00	0.07	0.27	0.04	6.666376413
	project F2	5.99	0.00	0.05	0.27	0.04	6.349568401
	project F3	6.24	0.00	0.07	0.26	0.04	6.617518835
	project F4	5.89	0.00	0.06	0.25	0.04	6.237443781
	project F5	5.78	0.00	0.05	0.25	0.04	6.126132858
	project F6	5.84	0.00	0.06	0.25	0.04	6.188586204
	project F7	5.89	0.00	0.05	0.26	0.04	6.230801616
	project F8	6.21	0.00	0.07	0.25	0.04	6.573776865
	project F9	5.90	0.00	0.05	0.26	0.04	6.248406475
	project F10	6.16	0.00	0.07	0.25	0.04	6.524919287
	project F11	5.47	0.00	0.05	0.25	0.04	5.812615347
	project F12	5.58	0.00	0.05	0.25	0.04	5.923534476
	project F13	5.59	0.00	0.05	0.26	0.04	5.942727456
	project F14	5.17	0.00	0.05	0.29	0.04	5.557025438
	project F15	4.50	0.00	0.03	0.27	0.05	4.853048456
A-C-D	project F1	5.43	0.00	0.07	0.24	0.04	5.769725757
	project F2	5.25	0.00	0.05	0.24	0.04	5.578573231
	project F3	5.38	0.00	0.07	0.23	0.04	5.720868179
	project F4	5.12	0.00	0.05	0.23	0.04	5.439103757
	project F5	5.06	0.00	0.05	0.23	0.04	5.371942059
	project F6	5.08	0.00	0.05	0.22	0.03	5.39024618
	project F7	4.86	0.00	0.05	0.22	0.04	5.17038759
	project F8	5.38	0.00	0.07	0.23	0.04	5.709213519
	project F9	5.20	0.00	0.05	0.23	0.04	5.512894709
	project F10	5.33	0.00	0.07	0.22	0.04	5.660355942
	project F11	4.53	0.00	0.05	0.22	0.04	4.831936248
	project F12	4.62	0.00	0.05	0.22	0.04	4.926971668
	project F13	4.57	0.00	0.05	0.22	0.04	4.88549255
	project F14	4.71	0.00	0.05	0.27	0.04	5.071394712
	project F15	1.38	0.00	0.03	0.19	0.05	1.646770489

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Article

Integrating Environmental and Economic Perspectives in Building Design

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Abstract: With increasing environmental damage and decreasing resource availability, sustainability assessment in the building sector is gaining momentum. A literature review shows that the related methods for environmental and economic performance, Life Cycle Assessment (LCA) and Life Cycle Costing (LCC), show great potential for answering a multitude of questions related to building performance. Prevalent topics are the implications of LCA and LCC for retrofit solutions and the trade-offs between environmental and economic considerations in building design. A detailed review of 30 case studies shows the range of differing result integration methods and sheds light on the use of monetary valuation of environmental indicators for an integrated assessment. While a quasi-dynamic approach, accounting for the changing value of money over time, is common in LCC, such an approach is largely absent from LCA. The analysis of common metrics shows that the studies employ strongly differing system boundaries and input parameters. Moreover, a clear description of the methodological framework is missing in most studies. Therefore, this research develops an "Eco^2" framework, integrating LCA and LCC for application in building design. Potential further developments for Eco^2 building assessment are related to extending the system boundaries by including mechanical systems and end-of-life phases, data collection and structuring, and streamlining the approach for continuous application to all stages of building design processes. Additionally, the influence on design decisions of employing temporal parameters in both LCA and LCC and of choosing particular result integration methods should be investigated further.

Keywords: building life cycle assessment; building life cycle costing; review; framework; environmental cost; integrated life cycle cost and emissions analysis

Citation: Schneider-Marin, P.; Winkelkotte, A.; Lang, W. Integrating Environmental and Economic Perspectives in Building Design. *Sustainability* **2022**, *14*, 4637. https://doi.org/10.3390/su14084637

Academic Editor: Ali Bahadori-Jahromi

Received: 11 February 2022
Accepted: 30 March 2022
Published: 13 April 2022

1. Introduction

In addition to the undisputed social and cultural value of buildings, the building industry represents a major part of the European economy, contributing to roughly 9% of the gross domestic product (GDP) of the European Union [1] and providing numerous jobs. At the same time, buildings contribute significantly to environmental problems; e.g., they emit 39% of global energy-related greenhouse gases [2]. Therefore, the building industry plays a major role in reducing emissions, while the economic viability of the building sector needs to be ensured.

To capture the full extent of the quality of a building, life cycle thinking (LCT), the concept of taking the entire life cycle of a product or system into account [3], rapidly gains importance in building design, especially for retrofit solutions [4–9]. The three related methods, (environmental) life cycle assessment (LCA), life cycle costing (LCC) and social life cycle assessment (sLCA), aim to achieve the triple bottom line of sustainability, addressing environmental, economic and social issues, respectively [10,11]. All methods have long been recognized to be part of a full sustainability assessment [12,13], a life cycle sustainability analysis (LCSA), striving to increase the sustainability of products and processes. The origins of the three methods do not lie in the building industry. sLCA is the newest method, recently developed as an extension to environmental LCA [14], and therefore less established than LCA and LCC [15]. LCA was first applied to evaluate packaging options [16], whereas the first application of LCC was in supporting procurement decisions by the US Department of Defense [17]. Hence, neither method was developed specifically for buildings, but each has been adapted to introduce the life cycle perspective into the building industry. Despite their relative maturity, neither LCA nor LCC are part of a standard design process [18], because several obstacles prevent their application. Both methods require detailed information about the future building, the development of scenarios for future events and circumstances, and a structure to communicate results to stakeholders. The data intensity of this process prevents their widespread use [19], worsened by the fact that LCA and LCC are currently developed and applied independently. This separation leads to methodological problems and misses opportunities to efficiently evaluate and optimize environmental objectives and life cycle costs in parallel.

Economic factors in a building design process often outweigh environmental considerations. An ecodesign process has been made mandatory for certain energy intense products by the European Union [20], stressing the opportunities of simultaneous energy and cost saving [21]. However, no building materials, rather only appliances and HVAC components, are part of this requirement. In building design, typical budgeting implies that the choice of a more expensive option in one area has to be compensated for by savings in another area. As LCA does not take such budgetary trade-offs into account, there being no set budget for environmental factors, it is difficult for designers and stakeholders to evaluate potential environmental improvements regarding their effectiveness [22]. Considering LCA and LCC in parallel helps to identify which life cycle phases and building parts carry economically viable environmental improvement potential. At the same time, an integrated approach exposes where and when environmental impacts can only be reduced at a high economic cost.

Because of their parallels and synergies, an integration of LCA and LCC has been subject of recent research, particularly in the building industry [19]. This paper provides an overview of the integration of LCA and LCC with regard to buildings, analyzing prevailing topics, integration methods, gaps and challenges. For result integration, we paid particular attention to studies expressing environmental factors in monetary terms, as converting all results to the same unit might provide a common ground for result integration. Based on the literature analysis we developed a framework for integrating LCA and LCC in the design process to bridge the gap and facilitate their use in building design.

2. Method

Firstly, a selective literature review on LCA + LCC (simultaneous LCA and LCC) in general, containing review and methodology papers, served as a basis to reveal common methods, existing frameworks and result integration. Twelve reviews on LCA + LCC or environmental and economic assessment were included, amongst further publications related to methodology. We verified that the referenced literature in the review papers pertaining to the building sector was included in the body of work identified by the subsequent keyword search. The reviews revealed general overarching topics in LCA + LCC research.

Subsequently, we conducted a comprehensive literature search for titles and keywords on Scopus, using, e.g., "LCA AND LCC AND construction", "LCSA AND construction", "LCT AND construction" as search terms in April 2021, adding recent publications in October 2021. Additionally, we searched with the term "building" in lieu of "construction" and with the spelled-out terms "life AND cycle AND assessment" etc. Citavi version 6.11 (www.citavi.com, accessed on 18 March 2022) software was used to organize and store literature items. We restricted the search to peer-reviewed journal publications, as these publications have been verified by the scientific community. The initial high number of publications (617 after duplicates were deleted) was then screened to ensure that both LCA and LCC were included; i.e., publications using a LCT or LCSA approach, but not applying LCA and LCC, were excluded from the review (Figure 1). We further reduced the remaining number of publications by filtering out the articles which exclusively concerned themselves with infrastructure and equipment, construction and demolition waste (CDW) or with analysis on an urban level, as we are focusing on the application in building design.

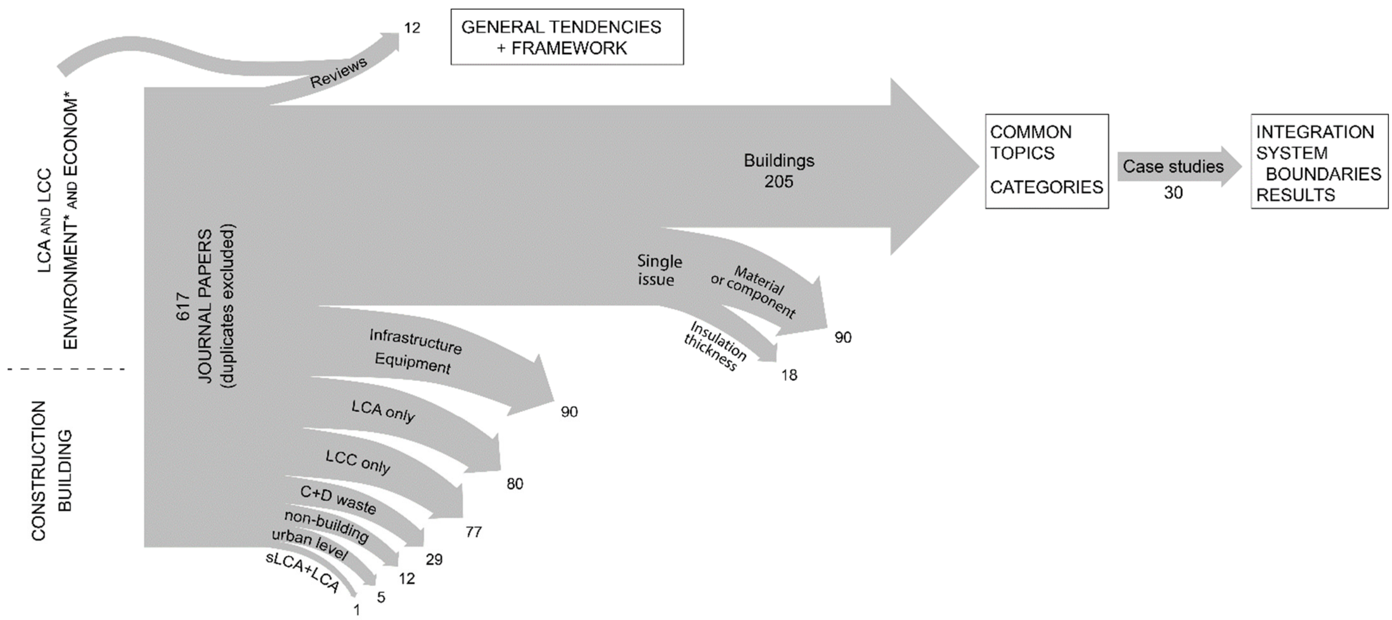

Figure 1. Workflow of the literature review.

In the final step, we investigated if the analysis was performed at the building level or on an element, component, or material level. Of the 108 publications we identified as single issue, 18 dealt with the optimization of insulation thickness based on environmental and economic criteria. The remaining 205 publications were categorized by titles and keywords to find overarching topics in LCA + LCC research.

By reading abstracts and looking for case studies we further identified 30 papers for a detailed analysis to answer the following research questions:

- What are the existing methods and/or frameworks for integrated LCA and LCC in building design?
- Are there common metrics (functional units, life cycle phases, study period) in the previous studies?
- How are results aggregated, compared and/or prioritized to support decisions in the building design process?
- What are the opportunities, challenges and gaps related to an economic-environmental analysis in building design?

As the literature analysis showed a lack of a common framework in existing studies, we developed such a framework to harmonize the methods, identifying parallel steps and synergies, providing a basis for transparency and comparability. Further conclusions from the literature analysis provide information about the steps proposed.

3. Literature Review

3.1. LCA and LCC

Unless only LCA and LCC are considered, they are seen as parts of an overarching goal in connection with other methods: LCA and LCC serve as tools in sustainability assessment [10,23] or in circularity evaluation [24,25]. Earlier reviews [25,26] consider LCA and LCC separately, as using both in parallel appears to be a more recent development. In the building sector, building information modeling (BIM) has been identified as a promising strategy to address the data intensity of the LCA and LCC processes, by aligning input data and managing the data intensity of the process [23,27].

LCA and LCC calculations are complex and require large amounts of data; i.e., their separate use potentially requires double the time and effort and is prone to errors [19]. Even if not fully integrated, their concurrent use, e.g., in the context of the same software tool, could reduce this barrier significantly. However, to arrive at meaningful results, aligning the setup and principles of LCA and LCC is necessary [28]. At the same time, the information about methodology and framework in published studies is very limited, both in LCA and LCC [29,30]. The use of differing frameworks and boundary conditions leads to a wide variation in result values [26], essentially impeding comparability and the transfer of results and experiences between studies.

The high number of recent reviews (Table 1) shows that the topic has received considerable attention, classifying the integration of LCA and LCC broadly into three strategies: (1) approaches using LCA and LCC in parallel at varying degrees of integration, (2) LCA as the leading methodology, including certain environment-related cost aspects, and (3) LCC as the base methodology, including some cost-related environmental aspects [31,32]. Miah et al. [33] extend this to six types of integration, subdividing parallel approaches into the three subtypes (1.1) independent use, (1.2) use as part of an overarching framework and (1.3) use with multi-criteria decision analysis (MCDA) as the integration method. Additionally, they add optimization and eco-efficiency to the picture, which shows that the focus is on the integration and further processing of results rather than the methodology itself. As part of an overarching framework, such as sustainability or circularity, LCA is the most frequently used life cycle method, followed by LCC, which has limited use, and sLCA being very rarely applied [15,24,25,30]. This almost exclusive focus on environmental issues does not sufficiently support implementation of sustainability or circularity, because economic issues act as the greatest barrier [25]. The reviews do not distinguish between the underlying (calculation) methods and the integration and representation of results as a basis for evaluation and, ultimately, for decision making. We add to this body of research by separating the underlying framework from result integration as two distinct but related characteristics. This emphasizes the importance of processing and post-processing results for LCA and LCC to be taken into account in building design processes.

Both LCA and LCC are system-wide approaches, as they share the life cycle perspective; hence, they call for the definition of spatial and temporal system boundaries and the use of corresponding databases [32]. Establishing a common basis aligns the use of data and facilitates the comparability of results. An integrated use has the potential to unify stakeholder perspectives, with LCA focusing on public goods such as human health or ecosystem quality, while LCC includes the (public or private) investor perspective [19,27]. If used in parallel, Hoogmartens et al. [10] recommend using fLCC and eLCA, as this avoids double-counting of impacts.

LCA and LCC results differ in their target values and units. LCA results typically include one or more environmental indicators, resource/energy use or potential environmental impacts caused by emissions. Mid-point impacts characterize emissions compared to a reference substance to show their contribution to a particular environmental problem, e.g., global warming potential (GWP), expressed in kg CO_2-eq. End-point impacts aim at quantifying the impact on areas of protection, e.g., human health, often expressed in disability-adjusted life years (DALY). Despite the large number of possible result values, there is limited use of environmental indicators, with most studies focusing on GWP and/or energy use [23,27,29]. In LCC, the target value is the minimum total cost in connection with an asset for its entire life cycle, measured in monetary terms. Additional possible indicators include the payback period, net savings (NS) or savings-to-investment ratio (SIR) [34]. In the context of building refurbishment, net present value (NPV) or discounted payback period are the most common result values [29].

Table 1. Recent reviews on environmental and economic life cycle assessment.

Title and Reference	Conclusions on LCA + LCC
Bridging the Gap Between LCA, LCC and CBA as Sustainability Assessment Tools [10]	• Identification of different LCA and LCC subtypes (low granularity): environmental, financial, social. • Parallel use of eLCA (environmental LCA) and fLCC (financial LCC) avoids double-counting of impacts.
Life Cycle Assessment and Life Cycle Cost Implication of Residential Buildings—A Review [26]	• Separate analysis of LCA and LCC studies reveals widely varying results.
A Hybridised Framework Combining Integrated Methods for Environmental Life Cycle Assessment and Life Cycle Costing [33]	• Focus on result integration. • Proposed framework: (1) decision-making perspective and goal, (2) system analysis, (3) system integration, (4) graphical interpretation.
Application of Life Cycle Thinking Towards Sustainable Cities: A Review [15]	• Limited LC studies on buildings with focus on economy, none on social issues, many on environmental issues. • Very few integrated schemes.
Exploring Environmental and Economic Costs and Benefits of a Circular Economy Approach to the Construction and Demolition Sector. A Literature Review [25]	• Focus on construction and demolition waste (CDW). • LCA the most frequently used methodology, rarely coupled with other analyses, although barriers to adopt a circular economy (CE) approach are economic.
Informetric Analysis and Review of Literature on the Role of BIM in Sustainable Construction [23]	• LCA, LCC, computational fluid dynamics (CFD) and certification systems are the most used methods for sustainability assessment. • Most studies focus on energy and cost.
Life Cycle Sustainability Assessment in Building Energy Retrofitting; A Review [29]	• Few details on the life cycle models used in reviewed papers. • Most prevalent indicators: net present value (NPV), discounted payback period (economic) and life cycle GHG (greenhouse gas) emissions (environmental)
Integrating Life Cycle Assessment and Life Cycle Cost: A Review of Environmental-Economic Studies	• Challenges: time and resource intensive methods; no wide-spread simplification; knowledge intensive. • Opportunities: enablers of great learning opportunities, common system boundaries, common objective and scope, common data collection and set of assumptions, alignment of LC-phases.
Integration of Life Cycle Assessment and Life Cycle Cost Using Building Information Modeling: A Review [27]	• Three main approaches for BIM integrated LCA and LCC: (1) using BIM to obtain bills of quantities and other data, (2) exporting data from BIM model to an external platform, (3) including information within the BIM model. • Energy use and carbon emissions most common environmental indicators for LCA.
Application of Life Cycle Sustainability Assessment in the Construction Sector: A Systematic Literature Review [30]	• LCSA studies focus on environmental issues. • Lack of methodology information on LCA and LCC in studies.
Assessment Methods for Evaluating Circular Economy Projects in Construction: A Review of Available Tools [24]	• LCA the most used assessment method for circularity. • Only one LCA and LCC study in building design identified [9], four studies using cost-benefit analysis (CBA).

To arrive at a single-point result for LCA, weighting is required, which is an optional step in the LCA process [35]. Normalization and/or weighting summarize LCA results, while enabling stakeholders to consider more than one environmental impact. The combination of LCA and LCC results requires yet another level of weighting and/or normalization after the weighting step in LCA, or in combination with it, identifying priorities and potential trade-offs between environmental and economic impacts. For the integration of single LCA + LCC (result) indicators, Huguet Ferran et al. [36] define the following three types: vector optimization, ratio method and weighted addition. Vector optimization graphically represents two indicators in relation to each other and can be used to compare alternatives and to identify dominant solutions. A commonly used ratio method is the calculation of eco-efficiency [37], evaluating economic value versus the environmental burden induced, thereby visualizing the potential trade-offs. Environmental LCC [38,39] is a type of weighted addition as it evaluates the net present cost of real cash flows; i.e., external costs are included if they are internalized or expected to be internalized in the near future. In that sense, it combines LCC and partial LCA, as it does not account for all external costs. All result integration methods except for MCDA need one indicator for LCA results; i.e., they require a weighting step in LCA, if more than one impact category is to be considered. Although weighting is discussed controversially in the scientific community, as it is seen as a value choice [40], it facilitates decision making, and several weighting methods have been developed [41]. Monetary valuation of environmental indicators could be an obvious choice to compare environmental and economic impacts, as it provides results in the same unit. However, it has been only rarely used in previous studies, because it is perceived as very complex, without established rules [19].

The building sector has been the most active of all sectors in the research area related to integrating LCA and LCC [19], as economic factors are seen as barriers for implementation of improved environmental quality [25]. However, all studies mention the lack of an integrated framework, although separate established methods for LCA and LCC exist.

3.2. Building LCA and LCC

Using the identification of overarching topics from the preceding section, all research papers were categorized by their titles and keywords, distinguishing analyses which exclusively used LCA + LCC or did so as part of a life cycle sustainability analysis (LCSA) or as two of the elements amongst methods related to LCT. A few papers did not use LCA but an environmental footprint (EF) method [42,43]. Additionally, two categories, "value" and "circular economy", were identified and added to the picture. The list of papers is available as Supplementary Material S1. Although a significant number of studies perform LCA and LCC in the context of a LCSA or as part of LCT, the majority of the studies state the use of LCA + LCC only (Figure 2). Very few publications mention the related approaches, circular economy (CE), environmental footprint (EF) or the more general term "value". Seven out of ten publications about the use of BIM for LCA + LCC use these two methods only, with three publications using LCA and LCC with BIM for LCSA.

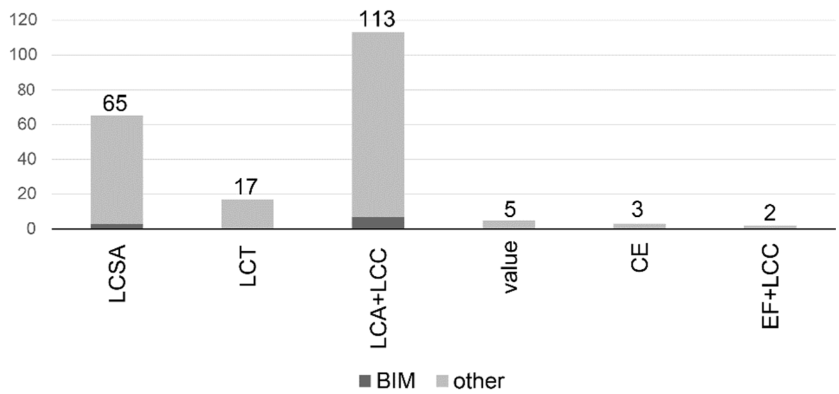

Figure 2. Number of publications on the environmental-economic assessment of buildings by related topic.

Figure 3 shows the rising number of publications in the past decade, as environmental problems are becoming more apparent. The steadily rising number is most apparent in LCSA, but also very visible in the use of LCA + LCC alone. As research into the environmental impacts of buildings has increased considerably in the past years [44], including economic assessments is a reasonable next step. Economic considerations are often cited as an obstacle to environmental improvement, hence the search for the best available trade-off between the two [45]. Although simultaneous environmental and economic benefits are possible, especially in the context of energy efficiency [8,46], none of the studies state this as their primary motivation.

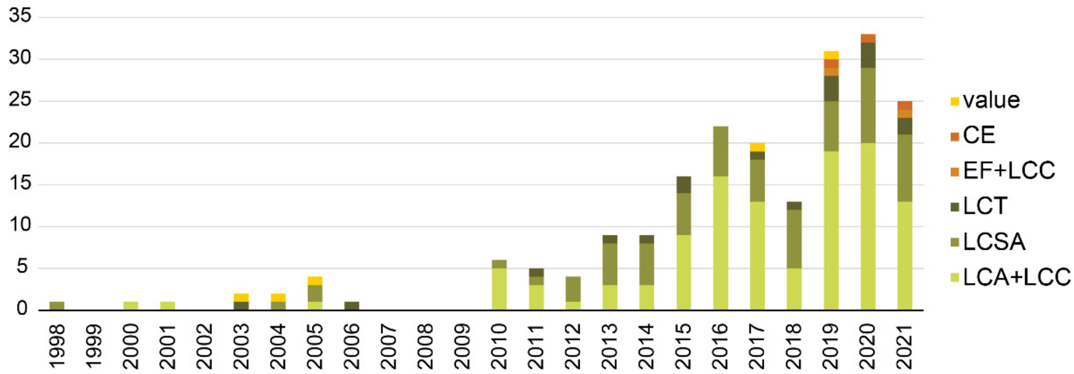

Figure 3. Publications on environmental-economic assessment of buildings by topic and year published.

3.3. Studies on LCA and LCC of Buildings

From the body of literature, we selected 30 studies on the use of LCA + LCC and the corresponding results as performance criteria, which assess one or more sample projects to investigate the potential influence of LCA and LCC criteria on building design (Table 2). Our selection is based on the availability of information about the LCA + LCC process, result integration and boundary conditions. Most case study buildings (21) are residential, with a few mixed-use and some non-residential building types. The subject of half of the studies is new construction, with the other half focused on building retrofit.

Table 2. Case studies on the environmental and economic life cycle assessment of buildings.

Title and Reference	Study Period (Years)	System Boundaries; Temporal: Life Cycle Phases	System Boundaries; Spatial: Elements and Processes	Process Integration and Methods	Goal or Research Question	Environmental Impact Indicators (LCA)	LCC Indicators	Temporal Parameters (DR Discount Rate)	Evaluation Method, Result Integration
Life-Cycle Energy, Costs, and Strategies for Improving a Single-Family House [47]	50	pre-use use demolition	construction materials appliances	independent, no standards mentioned	payback periods for energy efficiency measures	GWP	accumulated undiscounted cost, PV	DR: 0%, 4%, 10%; interest rate: 7%; energy escalation −1% to 4.2%	juxtaposition
Comparing Life cycle Implications of Building Retrofit and Replacement Options [48]	40	no repair and maintenance no end of life	retrofit: waste new materials; new construction: new materials	independent, no standards mentioned	retrofit or demolition?	GWP, solid wastes, air and water toxicity, resource use	capital cost, annual fuel cost, life cycle cost (NPV)	DR: 7%, energy escalation: 4% (SA with 10%)	juxtaposition, comparison checklist
Life-Cycle Carbon and Cost Analysis of Energy Efficiency Measures in New Commercial Buildings [46]	1, 10, 25, 40	LCA + LCC: construction repair replacement LCA: operation LCC: maintenance energy costs residual values	unclear	independent, no standards mentioned	cost-effectiveness of energy savings measures	GWP, CO_2 cost	NPV, adjusted rate of return (ARR)	DR: 3%	addition of CO_2 costs to LCC
Life Cycle Assessment and Life Cycle Cost Implication of Residential Buildings —A Review [49]	50, 100	construction operation maintenance disposal	no electrical wiring no plumbing no staircase	not specified; common inventory	flooring and roofing options with the best trade-off	GWP, water use, solid waste	NPV	DR: 3% and 6%	juxtaposition
Building Information Modeling Based Building Design Optimization for Sustainability [50]	50	focus on operation	ext. walls	BIM, no standards mentioned	minimize LCC and LCCE (life cycle carbon emissions)	GWP	NPV	real interest rate =−0.507%	multi-objective particle swarm opti- mization (MOPSO), Pareto-optimal solutions
Life-Cycle assessment and Cost Analysis of Residential Buildings in South East of Turkey: part 2—A Case Study [51]	50	LCC: home finance payments construction costs utility payments maintenance service end of life costs	walls flooring roof ceilings foundation basement doors windows appliances electrical systems	independent, no standards mentioned	optimum thickness of insulation	GWP	accumulated undiscounted costs	no discounting or price change	juxtaposition
Cost-Effective GHG Mitigation Strategies for Western Australia's Housing Sector: A Life Cycle Management Approach [52]	50	construction use	envelope	independent; LCA: ISO 14040-44; LCC:AS/NZS 4536:1999	cost-effective GHG emissions mitigation strategies for the construction and use	GWP, carbon tax	PV	DR 7%, inflation 3%	juxtaposition

Table 2. *Cont.*

Title and Reference	Study Period (Years)	System Boundaries; Temporal: Life Cycle Phases	System Boundaries; Spatial: Elements and Processes	Process Integration and Methods	Goal or Research Question	Environmental Impact Indicators (LCA)	LCC Indicators	Temporal Parameters (DR Discount Rate)	Evaluation Method, Result Integration
Assessment of Residential Building Performances for the Different Climate Zones of Turkey in Terms of Life Cycle Energy and Cost Efficiency [53]	30	A1–A3 B6	ext. walls ground slab roof windows	independent, 15643-2 mentioned for LC stages	optimum improvement of energy performance for different climate zones	GWP	NPV, discounted payback time SA with GWP damage costs	DR 6%, inflation 3,23%, PV degradation	juxtaposition
Construction Solutions for Energy-Efficient Single-Family House Based on its Life Cycle Multi-Criteria Analysis: A Case Study [54]	100	LCA: production/ construction operation maintenance dismantling recycling transportation LCC: investment, replacement costs annually recurring operating, maintenance, repair and energy costs end of life transportation	envelope walls windows doors roof foundations floor plumbing and sewage heating system, ventilation equipment electrical installation	independent, no standards mentioned	find the "best" solution for exterior walls	GWP, ODP	reduction of expenses	not specified	multi-criteria decision analysis
Lifecycle Costing of Low Energy Housing Refurbishment: A Case Study of a 7-Year Retrofit in Chester Road, London [55]	30	energy consumption maintenance repair	ext. walls roof floor	independent, no standards mentioned	compare retrofit solutions, determine payback time	GWP	NPV	DR 3,5%, SA 3,25%	cost per ton carbon saved
A Comparative Life Cycle Study of Alternative Materials for Australian Multi-Storey Apartment Building Frame Constructions: Environmental and economic Perspective [56]	60	LCA: product transportation end of life including CO_2 offset LCC: products manufacturing construction, maintenance demolition transportation final disposal	structural frame	independent; LCA: ISO 14040:2006; LCC:AS/NZS 4536:1999	compare various materials for constructing the structural frame: Laminated Veneer Lumber (LVL), 3 different manufacturing types, concrete and steel	GWP, AP, EP, fossil depletion, human-toxicity potential, carbon tax	NPV	DR 4,9% (SA 3% to 7%), 3% inflation rate (SA 1% to 5%)	juxtaposition, inclusion of carbon tax in LCC
The Influence of Secondary Effects on Global Warming and Cost Optimization of Insulation in the Building Envelope [57]	50	A1–A5 B1–B7 C1–C4 no indication if complete	ext. walls roof ground slab	independent, LCA: DIN EN 15804 mentioned	influence of secondary effects on insulation thickness optimization	GWP	NPV	DR 3% and 7%; energy price increase: index +2%	Pareto fronts

Table 2. *Cont.*

Title and Reference	Study Period (Years)	System Boundaries; Temporal: Life Cycle Phases	System Boundaries; Spatial: Elements and Processes	Process Integration and Methods	Goal or Research Question	Environmental Impact Indicators (LCA)	LCC Indicators	Temporal Parameters (DR Discount Rate)	Evaluation Method, Result Integration
Building Design-Space Exploration through Quasi-Optimization of Life Cycle Impacts and Costs [58]	25, 50, 100	embedded operational replacement	LCA + LCC: foundation floors ceilings ext. walls ext. finish int. walls roof windows doors LCC: HVAC system	independent, no standards mentioned	flexible design guidance	GWP	cost	no discounting or price change	weighting: minimization of costs, equal weighting of costs and impacts, minimization of impacts
Life Cycle Assessment and Life Cycle Cost of University Dormitories in the Southeast China: Case Study of the University Town of Fuzhou [59]	50, 75	construction operation, maintenance demolition	LCA and LCC: building equipment excluded	independent; LCA: ISO 14040	hot spots and improvement opportunities for university dormitories	ReCiPe midpoints (GWP and nine more indicators)	undiscounted cost	no discounting or price change	juxtaposition
Selecting Design Strategies Using Multi-Criteria Decision Making to Improve the Sustainability of Buildings [60]	100	no end of life	ext. walls roof insulation int. walls	not specified	evaluate design strategies (material choices; insulation thickness)	GWP	Cost savings; initial cost and inflation	not specified	Multi-criteria decision making (weighting by survey)
Streamlined Environmental and Cost Life-Cycle Approach for Building Thermal Retrofits: A Case of Residential Buildings in South European Climates [61]	50	end of life existing production new construction new heating/cooling maintenance	ext. walls and roof insulation and finishes windows	common database, common system boundaries, no standards mentioned	evaluate retrofit strategies in early design	ReCiPe (midpoint; GWP, ODP, AP, EP (marine and freshwater)	NPV and EAC (equivalent annual cost)	DR 1% to 8%	juxtaposition
Houses Based on Wood as an Ecological and Sustainable Housing Alternative-Case Study [62]	50	product construction process use end of life	Foundation vertical and horizontal structures roofing finishes	independent; LCA: EN 15978 LCC: ISO 15686-5	environmental and economic sustainability characteristics of selected construction variants	GWP, AP	NPV	DR 1%, 2%, 5%	juxtaposition
Trade-off Between the Economic and Environmental Impact of Different Decarbonisation Strategies for Residential Buildings [45]	30	product construction process use end of life	building construction building services	independent; EN 15804 life cycle phase definition used	contribution of different strategies to reaching climate goals	GWP	IRR (internal rate of return);	no discounting or price change; linear change of electricity mix emissions; 30% efficiency increase in manufacturing over the next 100 years	Pareto-front

Table 2. *Cont.*

Title and Reference	Study Period (Years)	System Boundaries; Temporal: Life Cycle Phases	System Boundaries; Spatial: Elements and Processes	Process Integration and Methods	Goal or Research Question	Environmental Impact Indicators (LCA)	LCC Indicators	Temporal Parameters (DR Discount Rate)	Evaluation Method, Result Integration
Life Cycle Assessment and Life Cycle Costing of Container-Based Single-Family Housing in Canada: A Case Study [63]	50	LCA: pre-use use demolition disposal LCC: initial investment operation maintenance repair	structure and finishes	independent; LCA: ISO 14044	life cycle impact of a container-based modular house compared to the conventional lightwood house built in Canada	GWP, AP, ODP, EP; smog potential, HH particulate, solid wastes generation	PV	DR 6%	juxtaposition, equal weighting
Whole Building Life Cycle Environmental Impacts and Costs: A Sensitivity Study of Design and Service Decisions [64]	60	A1-A3 B3-B4 B6-B7 no EoL	Superstructure, ext. and int. walls, roofs, windows, int. ceilings, floors and finishes, MEP of energy and water provision	framework = parallel use in one simulation setup	parametric assessment of building performance: LCA + LCC + energy modeling + seismic assessment	GWP	cost	not specified	separate indicators for LCA and LCC, sensitivity study
A Multi-Objective Optimization Model for Determining the Building Design and Occupant Behaviors Based on Energy, Economic, and Environmental Performance [65]	40	"the whole life cycle"	windows only	independent; LCA: ISO 14040	find optimal design strategies for each season	GWP	significant cost of ownership (incl. savings), NPV	Real discount rates: 2.68% interest growth rate, 0.98% electricity price increase, 1.97% gas price increase	Multi-objective optimization
Life Cycle and Life Cycle Cost Implications of Integrated Phase Change Materials in Office Buildings [66]	50	A1–A3 B6–B7 C1–C4	walls, floors and ceilings of one office unit	common inventory (OneClick LCA); LCA: ISO 14040, LCC ISO 15686;	benefits and costs of PCM in office uses	GWP, AP, EP, ODP, POCP	NPV, discounted LCC	DR 3%, general, energy, water inflation rate 2%	Juxtaposition
Is the Environmental Opportunity of Retrofitting the Residential Sector Worth the Life Cycle Cost? A Consequential Assessment of a Typical House in Quebec [67]	not specified	LCA: unclear LCC: investment, operations, maintenance, end of life	roof insulation, wall insulation, ground slab insulation, heating units	not specified	profitability of retrofit options	Impact 2002+: Human Health, Ecosystem quality, GWP, resources; ReCiPe (for result aggregation)	cost savings	DR 4%	Juxtaposition
Integration of LCA and LCC Analysis Within a BIM-Based Environment [68]	60 years	theory: streamlined (A1-A3) vs. complete (A1-D); case study: not specified	envelope int. walls int. floors	BIM, no standards mentioned	Design support	GWP, AP, EP, ODP, POCP, ADP	NPV	not specified	BIM framework

Table 2. *Cont.*

Title and Reference	Study Period (Years)	System Boundaries; Temporal: Life Cycle Phases	System Boundaries; Spatial: Elements and Processes	Process Integration and Methods	Goal or Research Question	Environmental Impact Indicators (LCA)	LCC Indicators	Temporal Parameters (DR Discount Rate)	Evaluation Method, Result Integration
Simulation-Based Multi-Objective Optimization of Institutional Building Renovation Considering Energy Consumption, Life-Cycle Cost and Life-Cycle Assessment [69]	50	not specified	Building envelope, energy-related systems (LCC only)	BIM, EN 15978 and EN 15804 mentioned for LC phases	optimize renovation strategies	GWP	life cycle cost (not specified)	not specified	Pareto fronts, Decision making; multi-objective optimization
Development of an Approach to Assess the Life Cycle Environmental Impacts and Costs Of General Hospitals Through the Analysis of a Belgian Case [70]	30	LCA: production construction use end of life LCC: investment cleaning maintenance replacements refurbishment operational energy and water use demolition waste treatment	building excl. surroundings	independent; LCA: EN 15804 and EN 15978	main drivers of the environmental impacts and costs of healthcare facilities, identify methodological obstacles for a quantitative assessment.	monetized results (GWP, ODP, EP, POCP, ADPE and 14 other indicators)	NPV	2% financial, 1% growth rate labour, 2% growth rate energy, 1% DR env. cost	total cost
To Retrofit or Not? Making Energy Retrofit Decisions Through Life Cycle Thinking for Canadian Residences [6]	25	LCA: construction manufacture installation operations disposal LCC: capital cost operation disposal	insulation windows energy systems	independent; LCA: ISO 14040	evaluate common upgrades; regional suitability of retrofits	GWP	payback period	DR 3%	eco-efficiency
Development of a BIM-based Environmental and Economic Life Cycle Assessment Tool [71]	50 years, 100 years	A1–A3 (streamlined) B6 excluded	content of the BIM model, MEP excluded	BIM: Common data repository, common inventory; no standards mentioned	proof of concept for LCA + LCC BIM integration	ADPE, ADPM, AP, EP, GWP, ODP, POCP, PENRE, PERT	NPV	DR 3%, 10% (100 years)	BIM; no integration of results
Environmental Costs of Buildings: Monetary Valuation of Ecological Indicators for the Building Industry [72]	50 years	LCA + LCC: A1–A3 B4, B6 C3, C4 D; LCC: B2 B3	structure finishes	parallel use, input aligned; LCA ISO 14040, DIN EN 15804	monetary valuation as a weighting method	monetized results (AP, ADPE, EP, GWP, ODP, POCP.)	NPV	DR 1,5% 2% price increase for building materials and services,	juxtaposition
Life Cycle Thinking-Based Energy Retrofits Evaluation Framework for Canadian Residences: A Pareto Optimization Approach [8]	25 years	LCA: manufacturing use disposal LCC: upfront cost operational cost	envelope energy systems	independent; LCA: ISO 14040	retrofit solution with minimum environmental and economic impacts	GWP	NPV (of operational cost savings)	DR 3%	Pareto optimization

LCA + LCC are applied to answer a wide range of questions, from the determination of payback periods for energy retrofits [47], finding optimal solutions for one building part (e.g., insulation thickness [51]) to optimizing an entire design space [58,64] or a group of building types [45]. Prevalent topics are the implications of LCA + LCC for retrofit solutions [6,48,55,61,67,69,73] and the trade-offs between environmental and economic considerations in building design [45,49,65,69].

3.3.1. Existing Methods and Frameworks

Despite the high number of publications and recent developments in the standardization of LCA and LCC, very few studies mention any standards as a basis for their calculations. For the LCA process, ISO 14040, ISO 14044, the building-specific EN 15978, or the building-product-specific EN 15804 are referred to [6,8,52,56,57,59,62,63,65,66,72]. Only three studies refer to an LCC standard; two Australian studies [52,56] refer to AS/NZS 4536, while one European study [62] refers to EN 15686-5. Moreover, underlying calculation metrics were rarely clearly described and are often missing altogether, making results difficult to interpret. The use of BIM implies an alignment of inventory data and offers the possibility to attach cost and environmental impact data directly to the materials and building parts in the BIM model. Beyond this assumption, the studies using BIM for the integrated calculation of LCA + LCC results [50,68,69,71] do not provide more details on calculation methods than the non-BIM studies considered. This lack of transparency inhibits validation and does not allow for general conclusions; i.e., each study answers its study question with a very specific setup.

Life cycle thinking should consider that buildings and the surrounding conditions change over their long lifetime. This calls for dynamic approaches in both LCC and LCA. In LCC, it is customary to account for the changing value of money over time by a quasi-dynamic approach with constant discount and price change rates. This does not, however, account for changing market or environmental conditions, technological or social improvements. Unlike in LCC, the prevalent method in LCA adopts a static approach, partially because perceived volatility is higher in economic data than in environmental data [19]. More recently, the literature on dynamic LCA has grown [74–76], which accounts for dynamic effects in LCA, including technological improvements [77], carbon uptake over time [78], dynamic occupant behavior [79] etc. In the building industry, most dynamic LCA approaches focus on greenhouse gas emissions, quantifying the changing effect of emissions over time [80], investigating changes in the electricity mix [75,81] or district heating [82] and their impact on operational emissions. Zhang [83] applies a quasi-dynamic approach to LCA by discounting the price of carbon emissions over time. Technological improvements and changes in the energy supply mix not only influence the emission factors for energy consumption directly, but also, indirectly, the emissions from material manufacturing. To quantify such effects on embedded emissions, inventory and impact data is recalculated by Potrč Obrecht et al. [77], showing that changes in the electricity mix can significantly influence GHG emissions embedded in materials. In studies considering both LCA and LCC, dynamic approaches in LCA are rarely present. Mangan and Oral [53] consider the degradation of photovoltaic systems in their environmental analysis. Conci et al. [45] assume a linear decrease in electricity mix emissions over time and a 30% increase in manufacturing efficiency over the next 100 years. Two studies apply discounting to environmental impacts after converting them to monetary values: for GWP only [56], or for a set of indicators [70]. One study considers a price increase for GWP [53]. Hence, dynamic effects for LCA are only rarely applied in environmental-economic calculations. However, if LCA indicators are monetized, discounting and/or price changes can be applied for a quasi-dynamic approach similar to LCC calculations.

3.3.2. Common Metrics

A frequently mentioned advantage of using LCA and LCC in parallel is the use of a common inventory [53,57,65]. This requires common spatial (building parts) and temporal (life cycle phases) system boundaries. Additionally, the study period, reference service lives (RSL) and the functional unit should be the same. In all studies, a common study period was specified for LCA and LCC, ranging from 1 year [46], as part of a sensitivity study, to 100 years [49,69,82,83]. 50 years is the most frequently used study period. Although the functional unit is very rarely explicitly mentioned, it can be derived from result representation. Most studies consider an entire building throughout its lifetime; some studies use one square meter, specifying the area either as living area [51], useful area [59] or useable floor area [72]. Only one study uses one square meter living surface area per year [45]. Although using area as the functional unit should make results more comparable between different buildings or building types, its use is not common. This again underlines the fact that the studies do not appear to aim for general applicability, but to answer specific questions about one building or building type.

The choice of temporal and spatial system boundaries varies strongly between studies, because including only the building parts and life cycle phases relevant for the research question reduces the data requirements for LCA and LCC. For a comparison of different options, this can be sufficient. Any systems which are the same for all options can be excluded, as they are irrelevant to the relative comparison. For instance, some studies are limited to the building skin [52,53,59,61,67,80] or a part of it [65], as they consider its influence on operational energy use, but not on other building systems. However, limited system boundaries miss information on the relevance of the study scope. In addition, if system boundaries are not stated clearly, results cannot be validated or compared with other studies. The temporal system boundaries in most studies are verbally described, often with differing terms for LCA and LCC, e.g., "pre-use" and "initial investment cost" [63]. In most studies, the terms used are vague (e.g., "the whole life cycle" [65], "use" [45,59,63,80]), impeding validation of results. The same holds true for the spatial system boundaries; i.e., the building parts and processes included or excluded are often unclear [46] or described in a non-standardized way. In all but one study [56], which is limited to the structural system, one (e.g., windows [65]) or more elements of the building envelope are included. Two studies include appliances [47,51] and eight studies include energy-related systems. Six of these studies include the respective embedded environmental impacts [6,8,45,54,64,67], whereas two studies include building systems only in LCC calculations [58,69]. In general, very little information is provided on the systems included or variations thereof.

The target values of the different studies show a homogenous picture: in all studies, minimizing GWP is stated as the environmental target (16 studies) or one of the targets (14 studies). Environmental indicators are aggregated to ReCiPe points [84] in two studies [59,61], and to Impact 2002+ [85] values in one study [67], with the rest of the studies using a selection of environmental impacts to represent LCA results, in some cases adding inventory indicators (e.g., energy, water use). In LCC, the prevalent target is minimizing the net present value (NPV), with the use of more than one indicator far less common than in LCA. Two studies use a static approach [51,58] and five studies lack information about temporal parameters (discount rate, inflation rate, price change rate) [50,55,68,82,83]. A few studies concerned with building renovation use payback period [6,53] or cost savings [67] as an indicator, based on PV calculations. Discount rates vary from 1% [61,62] to 10% [71], with both in the context of a sensitivity analysis. More common discount rates are 2% or 3%. Studies varying the discount rate state their strong influence on LCC results [49] and observe that lower discount rates emphasize the cost of building operation [62].

3.3.3. Result Integration

The strategies and results of the economic-environmental building life cycle assessments are not comparable, as each study establishes an individual evaluation framework to integrate LCA and LCC results. Most studies juxtapose one or more LCA indicator(s) and one LCC indicator, implicitly leaving prioritization to their target audience. As such, most studies identify trade-offs between environmental and economic factors without quantifying the impacts against each other. Four studies use Pareto fronts to identify Pareto-optimal solutions [45,50,57,69] and three recent studies employ MCDA and optimization [60,65,86]. An interesting approach is the calculation of life cycle cost per ton of carbon saved [55], as it determines GWP prevention cost of different measures within the building sector (in this case, retrofit options). This result integration is similar to eco-efficiency. It can only be employed if GWP is used as the single LCA indicator, but it reveals win-win situations when both cost and carbon is saved.

GWP stands as the single indicator for environmental impacts in the majority of building-related studies, with four studies [46,52,53,56] using carbon pricing or carbon taxes to monetize GWP results. Two additional studies not included in the detailed literature review use damage costs for carbon [9] or an estimated carbon price from the European Union Emissions Trading System (EU ETS) [87] to integrate results. Two studies add carbon tax or carbon pricing to LCC results to compare options [46,56]. Kneifel [46] concludes that the number of energy efficiency measures providing both life cycle cost and carbon savings increases when adding carbon tax to the life cycle cost equation. In contrast, adding carbon tax to the assessment of design alternatives leaves the number of economically viable options unchanged in [52]. For optimized solutions regarding LC energy use, CO_2 emissions and LCC, overall LCC decreased by a higher percentage compared to non-optimized solutions if carbon costs were taken into account [53]. For the evaluation of different structural materials, adding carbon cost and revenues does not change the ranking of options, neither does a variation in underlying parameters [56], as the option with the lowest life cycle cost shows the lowest GWP too. Hence, it depends strongly on the study setup and the values used for carbon pricing if monetization of this indicator has an influence on results.

From the environmental perspective, monetary valuation of more than one indicator is an indirect weighting method, as it applies monetary values to emissions or impacts to make them comparable. Although expressing environmental impacts in economic terms appears to be an obvious choice to compare or integrate LCA and LCC results from an economic standpoint, only two studies apply this method to more indicators than just GWP [70,72]. Both studies [70,72] conclude that the environmental costs are significantly lower than the corresponding financial costs, but it remains to be seen whether adding environmental cost to financial cost changes the ranking of projects. Our own study [72] finds that, for a set of office buildings, the environmental cost of GWP dominates the total environmental cost of the structure and finishes of these buildings, both for a maximum and a minimum valuation of a set of five indicators commonly used in Germany—GWP, AP, EP, ODP and POCP [72]. The study of Stevanovic et al. [70] analyses one hospital building. Despite the different set of monetary values used and a system boundary including operation, the study also concludes that GWP causes the highest amount of environmental cost amongst the indicators GWP, AP, EP, ODP, POCP, ADPE and ADPF. Therefore, monetizing only GWP appears to currently cover the majority of environmental cost. However, restricting evaluation to just one indicator neglects possible trade-offs with other environmental categories, especially when evaluating design options against one another. Moreover, as this only covers one part of the environmental costs caused, it is problematic when used in the context of an integrated environmental and economic assessment.

Although monetary valuation provides seemingly the same unit for both environmental and economic impacts, hence facilitating comparison and the visualization of trade-offs, two different cost types are displayed: LCC shows the financial cost an investor, owner or user is responsible for; whereas LCA reveals the external costs to society, e.g., for a deteriorating environment. Additionally, the results per emission or mid-point indicator differ strongly between studies [88]. Therefore, if used in a design process, sensitivity towards different valuation methods should be included.

3.4. Challenges and Opportunities

The analysis of 30 building LCA+ LCC case studies show a lack of a framework for an integrated approach on three levels. Firstly, most of the studies lack transparency as to the

LCA and LCC methods used. Secondly, both temporal and spatial system boundaries are not clearly described, as there is no common terminology used, for life cycle phases nor building parts and systems included. Moreover, some of the studies do not align the system boundaries for LCA and LCC, or leave it unclear as to whether the same system boundaries are used for both calculations. Thirdly, the studies show only limited result integration and lack reasoning for the choice of LCA indicators. This lack of a framework misses the opportunity to transfer results and experiences from one study to another, to validate results, and to draw general conclusions. This impedes a wide-spread application in design processes, as it suggests high variation in results and omits the question of whether a change in the framework also changes design recommendations.

If LCA and LCC point in the same direction, i.e., a solution has lower environmental impact and lower life cycle cost, it would be sufficient to use only one of the two methods for decision support. This can be the case with energy efficiency measures (e.g., [46,52]). The challenge of weighting LCA against LCC criteria, i.e., considering trade-offs, arises when the results show diverging tendencies, i.e., if environmentally favorable solutions show higher life cycle costs or low-cost solutions have a high environmental impact. In this configuration, a question of interest would be whether adding environmental cost to (financial) life cycle cost tips the scale towards a more environmental option, and, at which cost values this would be the case. With regard to this question, previous studies have looked into the impact of carbon tax, but no taxes or cost for further environmental impacts.

In an integrated framework, methods can enhance each other. For instance, the common practice of considering temporal parameters for future economic impacts can be included in LCA. Although the amount of emissions of a particular process (e.g., heat generation by fossil fuels) might not change significantly over time, the effect of these emissions can change depending on overall environmental quality. If this quasi-dynamic approach is used after monetizing environmental impacts, it provides an opportunity to treat temporal effects in parallel in LCA and LCC. Similarly, the clear definition of the steps required for LCA fills a methodological gap in LCC.

Opportunities include the integrated use of inventory data and methods (e.g., sensitivity analysis) and minimizing the risks of calculation mistakes due to contradicting data between LCA and LCC. Common challenges, such as uncertainty or complexity, can be treated in one step, identifying their overall relevance to a particular question. The greatest opportunity lies in the fact that integrated LCA + LCC calculations can answer a wide range of questions related to building design and operation, opening up the life cycle perspective for both environmental and economic considerations. This is particularly of interest when LCC and LCA do not show the same tendencies, i.e., if economic barriers exist for the implementation of more environmentally friendly solutions.

4. Integrated LCA-LCC Framework: Eco^2

This study complements previous studies by establishing a general framework for the application of LCA + LCC in the building design process to provide a background for future studies and, ultimately, improve comparability.

Although both methods have undergone standardization in recent decades, LCC lacks a general framework parallel to the steps of LCA established in EN 14040 [35]. However, in the context of the sustainability of buildings and constructed assets, EN 15643-4 [89] specifies the framework for LCC, and EN 16627 [90] the corresponding calculation methods. The parallel standards for the environmental assessment of buildings (EN 14643-2 [91] and EN 15978 [92], respectively) reference the more general EN 14040 [35] for LCA.

In addition to the lack of an integrated framework, the standards do not specify system boundaries, impact indicators, functional units, or calculation methods for individual life cycle phases; neither do they harmonize the interpretation and communication of results. Potential sources for specifications related to building LCA and LCC are building sustainability certification systems. Such systems, however, treat the two methods as separate criteria, impeding joint optimization of environmental and economic factors.

Figure 4 juxtaposes the LCA framework (not building-specific) and the building-specific LCC process, identifying parallel steps, though clarifying that the LCA framework is more general, whereas the LCC process does not so clearly separate the steps into a hierarchy. Impact assessment as a separate step is unique to LCA. Although cost calculation is economic impact assessment, the uncertainties related to impact pathways and associated damages of emissions are absent, as prices are subject to market mechanisms.

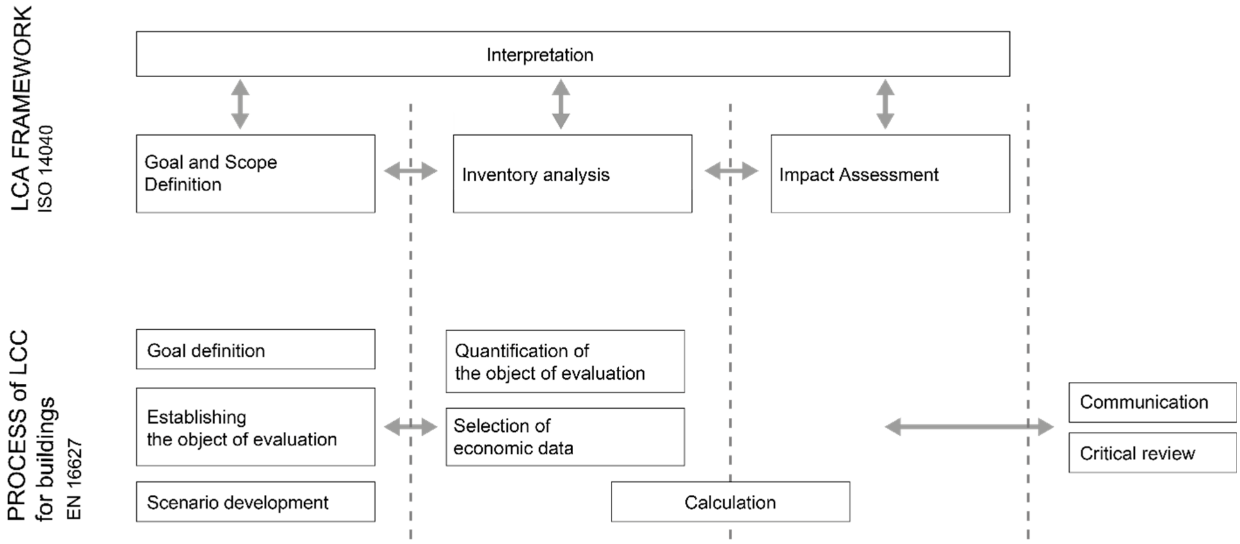

Figure 4. LCA framework per DIN EN 14040 and process of LCC per DIN EN 16627.

We propose to align the LCA and LCC processes, using the general LCA structure, adding methods from the LCC structure to harmonize the methodologies. This "Eco^2" framework developed for future studies integrates LCA and LCC, based on analysis of the literature, to facilitate decision support in building design (Figure 5).

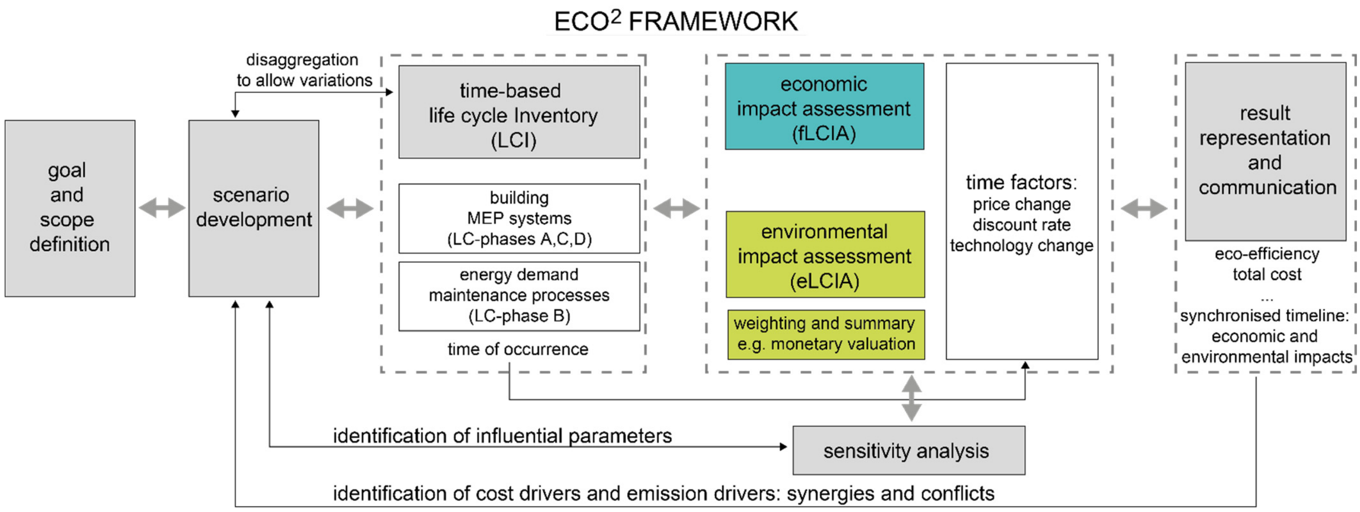

Figure 5. The Eco^2 framework.

LCA and LCC already share a number of common steps and requirements. To fully integrate both, harmonization of every step, as well as aligning both frameworks, makes best use of the opportunities of integration. For this purpose, input data is aligned in a time-based life cycle inventory; i.e., material and energy flows are only calculated once, and subsequently evaluated in environmental and economic terms. In addition, each process is associated with the time at which it incurs costs and/or emissions.

The framework includes weighting and summary of LCA results as one step to make the results comparable, and incorporates the temporal dimension of LCC into LCA. The steps are explained in more detail in the following sections (Sections 4.1–4.5), including conclusions drawn from the literature review in the previous section.

4.1. Goal and Scope Definition

The first step of the analysis defines the goal and scope, for both environmental and economic considerations, harmonizing the specification of the study period, defining equivalent system boundaries and the same functional unit. Especially in building design, the stakeholder group for the environmental aspects (e.g., the general public) often differs from the stakeholder group of the economic analysis (e.g., investor, building user). Harmonizing LCA and LCC aims to integrate both perspectives and enable solutions satisfying both interests. To increase comparability between studies, a detailed description of the system boundaries and the functional unit is recommended.

4.2. Common Metrics and Terminology

Although the life cycle for LCA and LCC is defined in a similar way by the respective standards (Figure 6), some fundamental differences exist. The existence of life cycle phase (module) A0, site and associated cost, in the economic, but not in the environmental life cycle, reveals that this phase might be regarded as irrelevant for LCA. This phase accounts for costs for the site and existing buildings, as well as planning costs. None of the previous studies explicitly included or excluded phase A0, but generally environmental analysis does not consider such site-related impacts, despite the fact that the choice of site might have a strong impact on the later life-cycle phases.

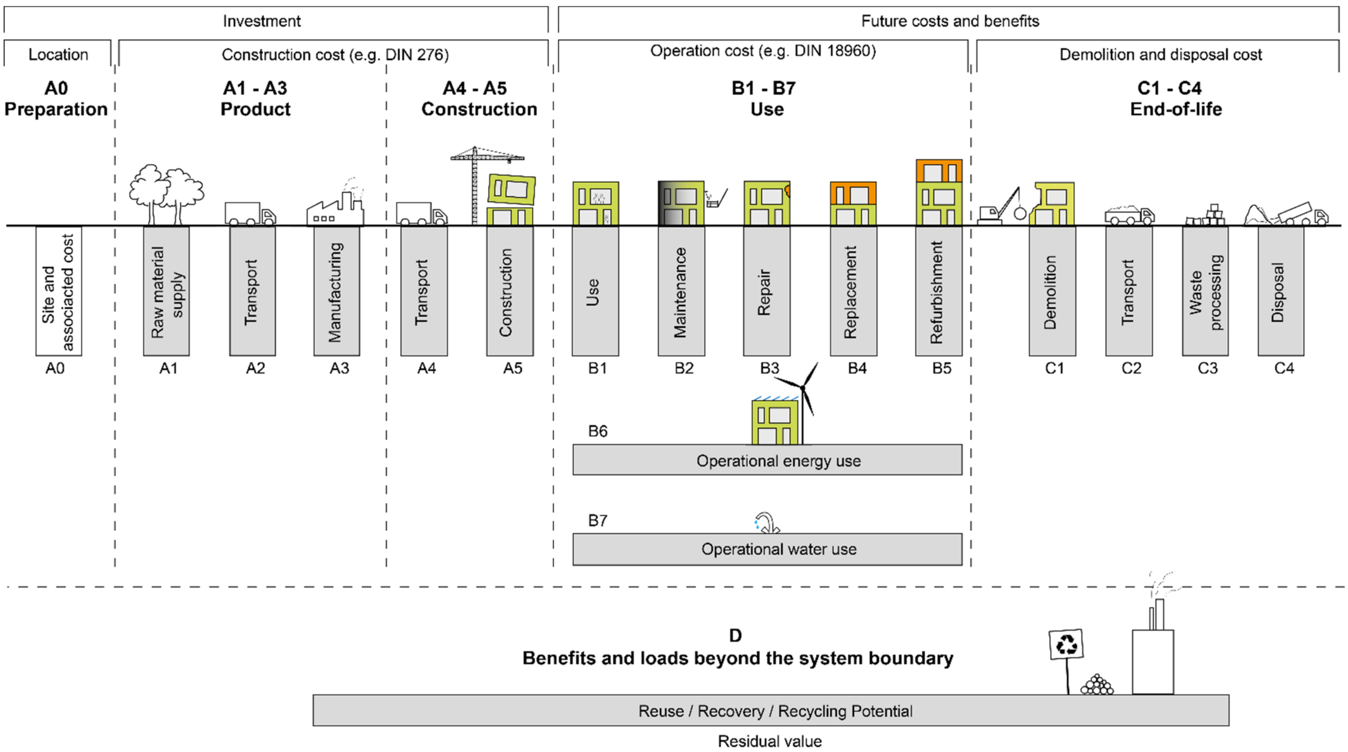

Figure 6. Combined life cycle phases according to BS EN 15978 and BS EN 16627; life cycle phase A0 only in BS EN 16627.

As cost drivers are not necessarily emission drivers and vice versa, different life cycle phases are excluded from LCA and LCC, respectively, as they are considered of lesser importance for one or the other. However, there is a lack of analysis on the distribution of impacts among life cycle phases in the reviewed studies. Few studies assess operational versus embedded impacts and costs, mostly concluding that the operational phase clearly dominates the environmental impact, while investment cost, i.e., production and construction, dominates life cycle costs [57,66,70,72].

Currently, there is no database for calculating all of the life cycle phases; only partial databases have been developed within a research context [61,71]. In general, LCC lacks data on end-of-life phases [25], while LCA lacks data on transport and construction processes, building inspection, repair and maintenance [45]. Data on the construction and use phases is more accessible for LCC, as labor costs largely determine construction processes, cleaning, inspection and maintenance. These are easy to assess economically, but difficult to look at in environmental terms, as labour is typically outside of the system boundary of LCA (e.g., worker commutes, food supply, consumption etc. are excluded). Therefore labour-intensive life cycle phases, such as A5 or C1, are often considered to contribute merely negligible environmental impacts [93], while potentially influencing LCC results [72]. Additionally, these life cycle phases are project-specific, and therefore excluded from, or incompletely included, in standard LCA datasets.

Life cycle phase D (benefits and loads outside of the system boundary) is part of LCA and LCC. Its inclusion in, or exclusion from, overall impacts is often discussed in the recent literature [94], as it is the phase where a circular economy should show its benefits. EN 15643-2 [91] allows phase D to be considered; i.e., this information is optional for environmental assessment. In LCA, materials with a high potential to avoid impacts (e.g., metals) receive many credits in phase D, along with materials serving as secondary fuels (e.g., wood, plastics) [95]. In LCC, materials with a residual value should also receive credits. However, these credits (e.g., for scrap metal) are marginal compared to investment costs [56]. With decreasing resource availability and an increasing interest in circularity, this should change in the future. In the Eco^2 framework, each life cycle phase, including phase D, should be calculated separately to shed more light on the significance of life cycle phases and drivers of impacts.

Decomposition of a building assists data collection, identifying drivers of costs and/or emissions, and supports comparability between studies [96]. Of 12 country-specific standards for building decomposition for the LCA purposes analyzed in [96], 10 are also applicable to cost calculation. The fact that most classification systems are already in use for both LCA and LCC should facilitate the alignment of naming and structure of a building and its sub-elements for Eco^2 calculations.

4.3. Scenario Development and Sensitivity Analysis

Scenario development is a central element of analysis and involves an iterative process. Initially, it is a result of the goal and scope definition, taking into account scenarios that experts deem decisive for economic and/or environmental impacts. Previous studies have investigated energy price change scenarios [47,48,55], decarbonization strategies [45], service decisions [64], PV degradation [53] and monetary valuation models [72]. Sensitivity analyses (SA) later in the process might identify additional influential parameters, calling for adapted or newly created scenarios varying these parameters, e.g., service lives and study period [97] or discount rates [49,56,57,61,62]. In a design process, these analyses can serve to determine the robustness of recommendations by answering the decisive question of whether a change in the framework or related parameters—discount rates, price increases, the inclusion of life cycle phase D, etc.—changes the ranking of possible solutions and, hence, design recommendations.

4.4. Impact Assessment and Two-Step Result Integration

In contrast to LCC results, which are expressed in market value, i.e., as currency, LCA has many possible assessment categories, with different units and without an agreed upon weighting system (see Section 3.3). Separating the weighting step in LCA from the weighting of LCA against LCC results increases transparency in the subsequent evaluation.

As such, the weight of environmental versus economic impacts can be made explicit and discussed. Monetary valuation for the weighting and summary of LCA results is the only calculation method that provides a common (currency) unit for environmental (eLCC) and economic (fLCC) evaluation. However, before simply adding the two values to support decision making, the high variation in monetary values assigned to environmental impacts has to be considered [70,72,88].

4.5. Visualization of Results

Result visualization, interpretation and communication are closely related and an important step towards reaching the initially defined goal of an Eco^2 study. However, result visualization in environmental-economic studies has not received much attention to date. For LCA alone, Hollberg et al. [98] identify 37 different visualization types and provide a comprehensive overview. This analysis can be partially transferred to Eco^2 result representation with the added challenge of visualizing at least two criteria.

Only a few of the reviewed studies did not visualize results, beyond displaying tables with numbers [65,68], whereas most studies used separate bar charts for environmental and economic results, sometimes superimposing results [8,45,52]. A more integrated way of visualizing the trade-off between environmental and economic criteria lies in scatter plots, plotting one LCC against one LCA indicator [8,50,57,58]. This requires one single indicator for economic and environmental results each, and allows for graphically identifying Pareto-optimal solutions. Rarely used visualizations are timelines [51,55,62], parallel coordinate plots [64] and heat maps [71]. These have potential for the comparison of alternatives within a design process and should be explored further.

5. Discussion

5.1. Gaps and Opportunities in the Literature Review

The literature search displayed a high number of studies treating environmental and economic issues in parallel. The large number of studies could only be analyzed regarding the overarching topics that LCA and LCC were applied to, without further details on the exact scope of the study. Our subsequent selection of building LCA studies was based on the criterion that a whole building should be included and that sufficient detail about the LCA and LCC analysis was provided. However, it is possible that other studies providing different insights were excluded if their titles or abstracts did not communicate such results. The 30 studies included should give a good overview of the currently prevalent topics, frameworks, and discussions of LCA and LCC in the building sector, but cannot claim to be a comprehensive overview.

The large number of studies and the increase in recent years reveals that life cycle topics are gaining momentum in the construction sector. More extensive analyses may follow, e.g., regarding the influence of regional factors in results, the influence of temporal parameters or the visualization of results. Our review is focused on, and limited to, the framework and methods, as well as result integration.

5.2. Opportunities and Future Developments of the Eco^2 Framework

We established the Eco^2 framework for building assessment to align environmental and economic life cycle approaches. This is intended to provide a background for future studies to improve comparability of calculations and results. Increased transparency in the methods and better result comparability would enable country- or region-wide comparison of environmental-economic factors, based on aggregated data from Eco^2 studies, as are performed [99] for environmental impacts. As both impacts depend on the surrounding conditions (e.g., electricity mix, energy and material market), decisive factors can differ between countries or regions, influencing recommendations for sustainability strategies.

The Eco^2 framework evaluates the building from a client perspective and is to be used in the design process. This entails that the decision process concerns a choice between materials currently available on the market, as the client does not usually influence the production process of the products. Looking at the results from a supplier perspective reveals opportunities in emissions reduction, which could potentially have larger-scale effects. For building owners and investors, as well as building product manufacturers, Eco^2 can provide a basis for an ecodesign [100] approach, specifically identifying areas for environmental improvement which are economically favorable. In that sense, Eco^2 introduces economic aspects to the ecodesign process. Conversely, Eco^2 complements economic decision making with environmental criteria, revealing decisions which might save financial cost, but cause high environmental impact. If the Eco^2 approach is applied to a scale beyond the scope of a single building, e.g., an entire neighborhood, city or country, it identifies system-wide economically efficient emissions reductions.

Regarding the application of the framework, several gaps identified in the literature review provide potential for further development. Firstly, sensitivity analyses, mostly conducted for price changes and discounting (see Section 4.3), should be aligned between LCA and LCC and extended to further aspects of life cycle uncertainty, namely, service lives of elements, length of study period, environmental and cost data. Secondly, both LCA and LCC calculations are subject to data gaps (see Sections 3.3 and 4.2). In LCA, these concern the life cycle phases specific to a building project—transport, construction, and disassembly (A4, A5, C1, C2)—and MEP systems, for which only a very limited number of studies has been conducted to date. In LCC, data for the value of a material at the end of its use period (phase D) is lacking, as are the costs for disposal or recycling. It is necessary to consider such costs to evaluate a building's potential contribution to a circular economy. Thirdly, the framework provides a structure for Eco^2 evaluation, but it does not remedy the complexity of life cycle calculations. Considering both environmental and economic impacts in parallel remains a data-intensive and time-consuming process. Further work is required to provide robust design assistance for early planning phases, when time and data are scarce, which, to date, has only been tackled separately for LCA [101,102] and LCC [103,104].

A full sustainability assessment adds social LCA (sLCA) to the picture [12], an aspect lacking in the studies to date [15]. The social cost of labor could potentially be significant, especially in the building sector, as it is one of the sectors most prone to labor exploitation in Europe [105]. Additionally, the social cost of construction processes has been highlighted in several studies [106]. The common practice of excluding life cycle phases A5 and C1 from building LCA does not allow the accounting of these costs. As with accounting for the environmental impacts of materials and operation, such considerations might provide a counterweight to LCC, and allow for a broader view on construction activities. However, in sustainability studies, special care has to be taken to avoid the double-counting of impacts, by distinguishing between external and already internalized costs.

6. Conclusions

The literature review showed that the number of LCA + LCC studies has been steeply rising in the past decade, as sustainability concerns in the building sector are becoming increasingly apparent. Most studies related to the building sector use LCA + LCC as a way to identify environmental and economic factors in parallel, followed by a large number of studies which use both methods in the context of life cycle sustainability assessment. Fewer studies adapt a wider perspective, such as life cycle thinking, circular economy, or value. LCA + LCC can answer a wide range of questions related to new buildings, refurbishment, and operation. Most studies state their goal as to identify the best available trade-off between economic and environmental considerations, assuming a dysfunctional market with environmental solutions more expensive than less environmentally friendly ones. Nevertheless, simultaneous environmental and economic benefits are possible, especially in the context of energy efficiency. It is these win-win solutions that bear the potential of increasing the sustainability of the construction sector by reducing environmental and economic burdens in parallel.

Presently, investigation of life cycle environmental and economic impacts for buildings in parallel is time-consuming and requires expertise in both LCA and LCC, which limits the application of an integrated approach to research studies and causes life cycle impacts to be mostly disregarded in design processes. The literature review showed a large variation in system boundaries and frameworks, as each study is set up to answer a particular question, specific to the building type and location under investigation. However, even in a research context, studies lack transparency and clear frameworks, and are rarely applied to overall design questions, limiting their comparability and overall applicability. Our study proposes the Eco^2 framework to facilitate the process by harmonizing environmental and economic calculations, to increase transparency and transferability. Design alternatives can thus be developed for Eco^2 rather than for LCA and/or LCC in an isolated way, and provide leverage towards environmentally favorable solutions, especially if they prove to be economically sound as well. Additionally, the Eco^2 framework offers a way to clearly communicate and discuss the cost and benefits of emissions reduction. In this framework, the gaps in previous studies could be systematically filled. Firstly, system boundaries can be extended to elements and life cycle phases which are, to date, rarely included in studies, such as including MEP systems and interiors, or end-of-life phases. Secondly, data collection and structuring are important topics, both for inventory as well as environmental and economic impact data. This can be instrumental in, thirdly, streamlining the approach for continuous application to all stages of building design processes, at increasing levels of development. Lastly, sensitivity analyses should be systematically applied to investigate the robustness of decision support. In this context, the influence on design decisions of employing temporal parameters in both LCA and LCC, and of choosing particular result integration methods, should be investigated further. Our next step is to apply this framework to a case study including design options for building structure and finishes, as well as mechanical systems, and to test the influence of different parameter choices on design recommendations.

Against the backdrop of recent developments regarding, for instance, the introduction of CO_2 taxes, first steps towards an internalization of external costs for environmental degradation and damage have been taken. Eco^2 creates an integrated life cycle evaluation methodology, which has the potential to support the urgent transformation of the building sector towards a fundamentally sustainable built environment.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su14084637/s1.

Author Contributions: Conceptualization, methodology, formal analysis and investigation, data curation, writing—original draft preparation, visualization: P.S.-M.; writing—review and editing: A.W. and W.L.; supervision: W.L.; funding acquisition: W.L. and P.S.-M. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Deutsche Forschungsgemeinschaft (German Research Foundation, DFG) under grant FOR2363—project number: 271444440.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: Thank you to Pia Marciano for her help with text editing and to Ana Klainsek for her help with the Sankey diagram. For their scientific input and valuable feedback, we sincerely thank Leander Schneider and Inger Andresen. We also thank four anonymous reviewers for their valuable input to the manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

ADPE	abiotic depletion potential for non-fossil resources
ADPF	abiotic depletion potential for fossil resources
AP	acidification potential
BIM	building information modelling
CBA	cost-benefit analysis
CFD	computational fluid dynamics
CDW	construction and demolition waste
CE	circular economy
EF	environmental footprint
eLCC	environmental life cycle costing
EP	eutrophication potential
FEP	freshwater eutrophication potential
fLCC	financial life cycle costing
GHG	greenhouse gas
GWP	global warming potential
HH	human health
HVAC	heating, ventilation, air conditioning
LCA	life cycle assessment
LCC	life cycle costing
LCCE	life cycle carbon emissions
LCSA	life cycle sustainability analysis
LCT	life cycle thinking
MEP	mechanical, electrical, plumbing
NPV	net present value
NS	net savings
ODP	ozone depletion potential
POCP	photochemical ozone creation potential
PV	present value
RSL	reference service life
SA	sensitivity analysis
SIR	savings to investment ratio
sLCA	social life cycle assessment
TAP	terrestrial acidification potential

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A Temporal Perspective in Eco² Building Design

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Abstract: The architecture, engineering and construction (AEC) sector has great potential and responsibility for reducing its considerable resource consumption and high share of global emissions. However, economic factors are often cited as barriers to more environmentally friendly solutions in building design. Hence, environmental and economic life cycle assessment (LCA and LCC) are of utmost importance in building design. They serve as the base methodologies for what we call the "Eco²" framework. In this context, monetary valuation of multiple environmental impacts allows to integrate the results as a basis for design decisions. A case study representative of small-scale office buildings in Germany illustrates the Eco² framework and shows the influence of temporal parameters (discount rates and price changes), as well as of differing monetary valuation, on the ranking of design options. Varying the temporal parameters affects the ranking of different solutions for the structure and finishes of the case study building but not for its mechanical, electrical and plumbing (MEP) systems and operation. However, the ratio of environmental life cycle cost (eLCC) to financial life cycle cost (fLCC) is significantly higher for MEP systems and operation than for the structure and finishes. This investigation shows that it is possible to achieve simultaneous emission and cost savings, whereas temporal factors can decisively influence decision making in design processes.

Keywords: building life cycle assessment; building life cycle costing; discounting; environmental cost; integrated LCA and LCC; dynamic LCA; MEP systems

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Citation: Schneider-Marin, P.; Lang, W. A Temporal Perspective in Eco² Building Design. *Sustainability* **2022**, *14*, 6025. https://doi.org/10.3390/su14106025

Academic Editors: Erwin M. Schau and Eva Prelovšek Niemelä

Received: 6 April 2022
Accepted: 9 May 2022
Published: 16 May 2022

1. Introduction

Demand for comfortable indoor environments is growing globally, but the architecture, engineering and construction (AEC) sector is already responsible for 37% of global GHG (greenhouse gas) emissions [1] and consumes a large share of Europe's material resources, especially minerals and metals [2]. The sector is falling short of reducing emissions and resource consumption [3] while trying to meet global demand. Frequently, economic barriers are cited as a reason for the slow change in the AEC sector [4]. Hence, to speed up the transition, it is not sufficient to calculate emissions for different building solutions, disregarding economic factors, or vice versa.

Additionally, a long-term life cycle view urgently needs to replace the prevalent short-time perspective in building design. This entails considering life cycle costs rather than investment costs only and life cycle emissions rather than emissions caused by operational energy use only, the latter being in the focus of current building regulation [5]. For both perspectives, life cycle methods have been established: life cycle assessment (LCA) for the emissions perspective and life cycle costing (LCC) for economic calculations. Integrating both into design processes offers the opportunity to identify win–win situations and to indicate economically viable emissions savings to building clients and stakeholders. From a policy perspective, solutions with high emissions saving potential, which are currently economically unattractive, can be supported, e.g., by financial incentives.

Work on both LCA [6] and LCC [7] in green building design, as well as on a parallel use of both [8], has increased considerably in the past decade, but there are still methodological gaps for an integrated use, and neither method is part of standard building design processes. Therefore, we developed what we call the "Eco^2" (ecology × economy = Eco^2) framework [9] for an integrated use of LCA and LCC in building design. This framework uses a common life cycle inventory for LCA and LCC, mapping environmental and economic data to it, as well as common data, such as reference service lives (RSLs). For result integration, monetary valuation of impacts is used. Here, we illustrate and test the framework with a case study. The case study was selected to fill information gaps in previous studies by including mechanical, electrical and plumbing (MEP) systems in both LCA and LCC calculations and their respective embedded and operational impacts. Additionally, we developed a limited database for this case study to allow for the combination of differing building subsystems. Previous studies have tended to consider either tradeoffs between embedded and operational emissions and cost [10] or optimization of envelope energy systems and emissions [11], disregarding embedded emissions in energy systems, although in a real design process, all aspects need to be taken into account.

As operational energy use has been identified as one of the major causes of GHG emissions while bearing the most economically favorable emissions savings, the EU established ecodesign regulations for some energy-consuming appliances (e.g., heating and cooling appliances) [12] but neither for buildings nor for building products. Ecodesign specifically targets financial savings by redesigning products for emissions saving and has proven that savings potential is considerable.

Using monetary valuation for result integration has only been tested in a few studies [13,14] but bears the opportunity to juxtapose environmental and economic goals. An integrated use of LCA and LCC whilst valuing emissions in monetary terms enables transfer of the quasi-dynamic approach from LCC to LCA, thereby considering identical scenarios for both environment and economics. Fully dynamic LCA and LCC require dynamic inventories, as well as the inclusion of uncertainties in future developments, such as the marginal effect of emissions [15]. Dynamic inventories for LCA consider changes in energy supply [16] and/or the increase in production efficiency [17], whereas for LCC, such inventories should include material-specific criticality. A quasi-dynamic approach simplifies this process by introducing gradual annual changes. Their effect is exponential and allows for variant studies testing different scenarios. Adding temporal parameters into LCA has not previously been implemented in simultaneous building LCA + LCC evaluations. Therefore, we aim to test the influence of discounting and price change assumptions, as well as the use of differing monetary values for emissions, on the comparison and resulting ranking of proposed building solutions.

A fully integrated Eco^2 approach has the potential to show the value of emissions savings in design processes and identify solutions with low-cost or even profitable emissions saving. Introducing the life cycle perspective shifts the focus from limited investment cost considerations to a wider spectrum of evaluation. As a consequence of the future perspective, temporal factors allow for consideration of uncertainties in the development of the environment and the economy. In this context, the main question of this research is how and to what extent such temporal factors influence decision making in building design.

2. Method: Eco^2

Life cycle assessment (LCA) and life cycle costing (LCC) are at the core of the Eco^2 framework [9]. We employ this framework, using monetary valuation as a weighting method, to arrive at one value for LCA results, and varying temporal parameters to test their effect on design recommendations.

2.1. Goal and Scope

An office building with a gross floor area of approximately 1200 m^2 serves as case study. The FTmehrHAUS has three floors and was built in 2016. The building has a simple rectangular shape with a regular façade and is representative of a standard small office building in Germany [18]. It served as a case study in the Early BIM project [19] for the investigation of opportunities of using semantically rich BIM models in early design phases and in related studies [13,20–25] because detailed information about the building has been made available by the owner. Table 1 shows the relevant parameters and boundary conditions for the Eco^2 analysis.

Table 1. Case study parameters.

Parameter	Elements Included	Description	Variations
Spatial system boundary	CG 300	all building parts	construction type, material choices
	CG 400	MEP, incl. HVAC; lighting	energy supply system
Temporal system boundary	50 years		
	LCA: A1-A3; B2-B4; B6; C3-C4; D		D included/excluded
	LCC: A1-A5; B2-B4; B6; C1-C4; D		
Data source LCA	Oekobaudat 2020-II	[26]	
Data sources LCC	Baupreislexikon Baukostenindex (BKI) Sirados	[27] [28] (few data gaps CG 300) [29] (few data gaps CG 400)	
Operational impacts	heating, cooling, lighting	[30] electricity generated on-site subtracted from monthly electricity consumption; surplus fed into the grid	energy supply (HVAC system)

The case study looks at the following questions:

- Which material and energy supply solutions result in the lowest environmental impacts, expressed in environmental life cycle costs (eLCC) and/or the lowest financial life cycle costs (fLCC)?
- Do temporal parameters change recommendations?
- Does monetary valuation change recommendations?

2.2. Life Cycle Phases

Currently, no database provides inventory and impact data for calculating environmental and economic impacts in all life cycle phases, and different phases are excluded from LCA or LCC [9]. For instance, life cycle phases A4 (transport gate to site) and A5 (construction) are rarely accounted for in LCA, whereas it is customary that these values are included in the construction prices by default but they are not listed separately. Consequently, C1 (demolition) and C2 (transport site to waste processing or disposal) are included in LCC but disregarded in LCA. For our study, this discrepancy in system boundaries is accepted (Table 1), as previous studies have found that environmental impacts from these phases are comparatively small.

Life cycle phase D (benefits and loads outside of the system boundary) is controversially discussed in the literature [31], as it is outside of the system boundary of the building; hence, benefits from phase D should potentially be accounted for in a different system. On the other hand, phase D contains important information on the circularity potential of buildings. In LCA, recyclable virgin materials that show high impacts in the product stage (A1–A3) receive credits in phase D for avoided impacts (e.g., metals) [32]. Additionally, for materials serving as secondary fuels (e.g., wood and plastics), the offset of emissions against the current energy mix is credited. Materials with a high residual value because of their scarcity or energy-intensive production, such as metals, should also receive financial credits in LCC. However, these credits (e.g., for scrap metal) can be very small compared to investment cost [33], and they happen in the distant future. Moreover, in the databases used for this study, disposal costs include potential material values but do not consider them separately, i.e., if there are economic benefits for phase D, they are merged with the demolition and disposal cost. This is in line with the findings of [4] that the environmental impacts of the end-of-life phase are disproportionally more intensely studied than the economic impacts. For this study, each life cycle phase, including phase D, is calculated separately to allow for the tracking of drivers of impacts.

2.3. Functional Unit

Although both LCA and LCC use a functional unit, which, in principle, facilitates comparability, this is not always specified in studies and can even vary within a sustainability certification system. Specifically, the German building sustainability certification systems DGNB and BNB express LCA results as indicator per m^2 NFA (net floor area) per year, where indicators include, among others, GWP and acidification potential (AP) [34,35]. The unit for LCC results, on the other hand, is EUR per m^2 GFA (gross floor area) [36,37].

2.4. Building Decomposition

In the German context, the two commonly employed systems for building decomposition were developed for cost calculation and cost monitoring. One system [38] subdivides the building into so-called cost groups (CGs). The second common system, employed primarily in bidding and construction, focuses on trades [39]. It is less apt for environmental (material-focused) evaluation, as, firstly, granularity is too high for design phases with open decisions, and secondly, alternatives are harder to compare, as they are ordered by the trade involved rather than equivalent building parts. CGs are frequently used for disaggregation of the building in LCA [40], as this subdivision is already familiar to designers from cost estimation and calculation. CG 300 (structure and finishes) and CG 400 (MEP systems) are directly related to the building. CGs are applicable to all embedded (material-related) impacts, whereas for impacts caused by operational energy consumption, a separate category, life cycle phase B6, is necessary. However, B6 is closely linked to CG 400, as the type of MEP system has a major influence on emissions in phase B6 [41].

2.5. Scenario Development

For the scenario analysis, the decisive question is whether a change in the parameters, such as discount rates, price increases, or the inclusion of life cycle phase D, changes the ranking of possible solutions. This investigation shows whether the framework influences an environmental–economic recommendation to stakeholders.

Figure 1 shows the construction and energy source variations for the sample project. We aim to cover the majority of standard construction parts and a selection of heating systems. As quantifying the tradeoff between energy standard and embedded emissions is not the primary goal of this study, we excluded the mutual influence of CG 300 and CG 400 + B6. Therefore, we kept the energy standard and the heat/cold distribution constant. For example, all variations of the building contain floor heating. As such, we can consider the variations of CG 300 and CG 400 + B6 separately. For a decision-making process, these subsystems can be optimized separately and recombined to obtain a complete solution.

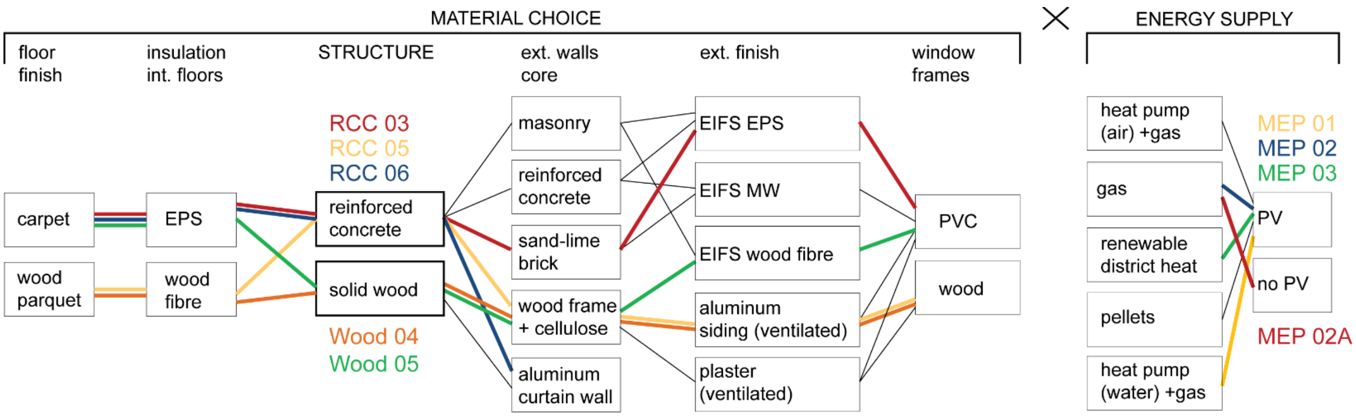
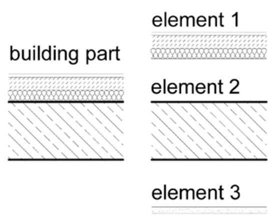


Figure 1. Characteristics of variations of the case study; colours correspond to the solutions represented in timelines (Section 3).

2.6. Time-Based Life Cycle Inventory

To integrate the two different life cycle approaches, LCA and LCC, it is necessary to use the same bill of quantities for the life cycle inventory and an integrated database for both environmental and economic values with the same base year. Matrices showing the data for each life cycle phase and each building element or material are at the core of the LCI, containing all necessary information for the subsequent impact assessment (Figure 2).



		non-recurring						recurring	
	RSL	A1-A5	B4 (a)	B4 (b)	B4 (2a)	C1-C4	(D)	B2	B3
material 1.1	a	x	x		x	x	(x)	x	x
material 1.2	a	x	x		x	x	(x)		x
material 1.3	b	x		x		x	(x)		x
material 2.1	>S	x				x	(x)		x
material 2.2	>S	x				x	(x)		x
material 3.1	b	x		x		x	(x)	x	x

Figure 2. LCI matrix for a building part. RSL = reference service life, S = study period; a = number of years (RSL) smaller than S and less than S/2; b = number of years (RSL) smaller than S and greater or equal to S/2.

2.7. Impact Assessment

LCA and LCC were calculated in parallel through adata collection specifically created for this study. We limited environmental data for this study to materials and processes contained in Oekobaudat [26]. The life cycle inventory for the environmental calculation was also used for the life cycle cost analysis, i.e., only products and processes available in Oekobaudat were included in cost calculations to avoid differing system boundaries. Cost data were sourced from a commonly used dictionary of construction prices (Baupreislexikon [27]), with a few remaining data gaps filled by BKI [28] and Sirados [29]. Building elements were priced (investment cost and replacement cost), and maintenance and repair costs were tied to specific building elements (e.g., cleaning costs were associated with surfaces). The data source for the latter is the German certification system BNB [37]. End-of-life costs were attached to the specific building material or building part to be exchanged or demolished. These cost values are based on the assumption of careful disassembly and separation of building materials. The available cost data do not allow for differentiation between demolition (C1), transport (C2), processing (C3) and disposal (C4) costs or credits for material value (phase D), as they provide an aggregated cost value for end of life.

The operational energy demand for heating, cooling and lighting (phase B6) was calculated on the level of the whole building according to DIN V 18599 [30]. Environmental impacts and costs were assigned to operational energy consumption per year. On-site electricity generation was deducted from electricity demand on a monthly basis. Surplus electricity was sold back to the grid per the current feed-in tariff, and the difference in emissions to the German electricity mix was credited. Oekobaudat [26] provides values for the related emissions; cost data are taken from the BNB specifications [37] and converted to the base year 2020. For the electricity mix, the scenario present in Oekobaudat was used as a basis for determining how emissions from electricity generation might change over time as the share of renewable energy increases (see Section 2.8.2).

2.8. Interpretation and Communication of Results

The first step to interpret the results is to choose solutions that represent extremes in environmental or financial terms in order to simplify results and to reduce the number of choices to communicate to stakeholders. In a second step, timelines (Figure 3) represent the reduced number of solutions. This LCA result representation in a timeline is not common practice [42] but provides valuable insights into potential future developments. Step three subsequently identifies the elements causing a high share of eLCC and/or fLCC and the corresponding points in time. If applicable, in a fourth step, additional solutions combining favorable building parts and/or materials can be generated.

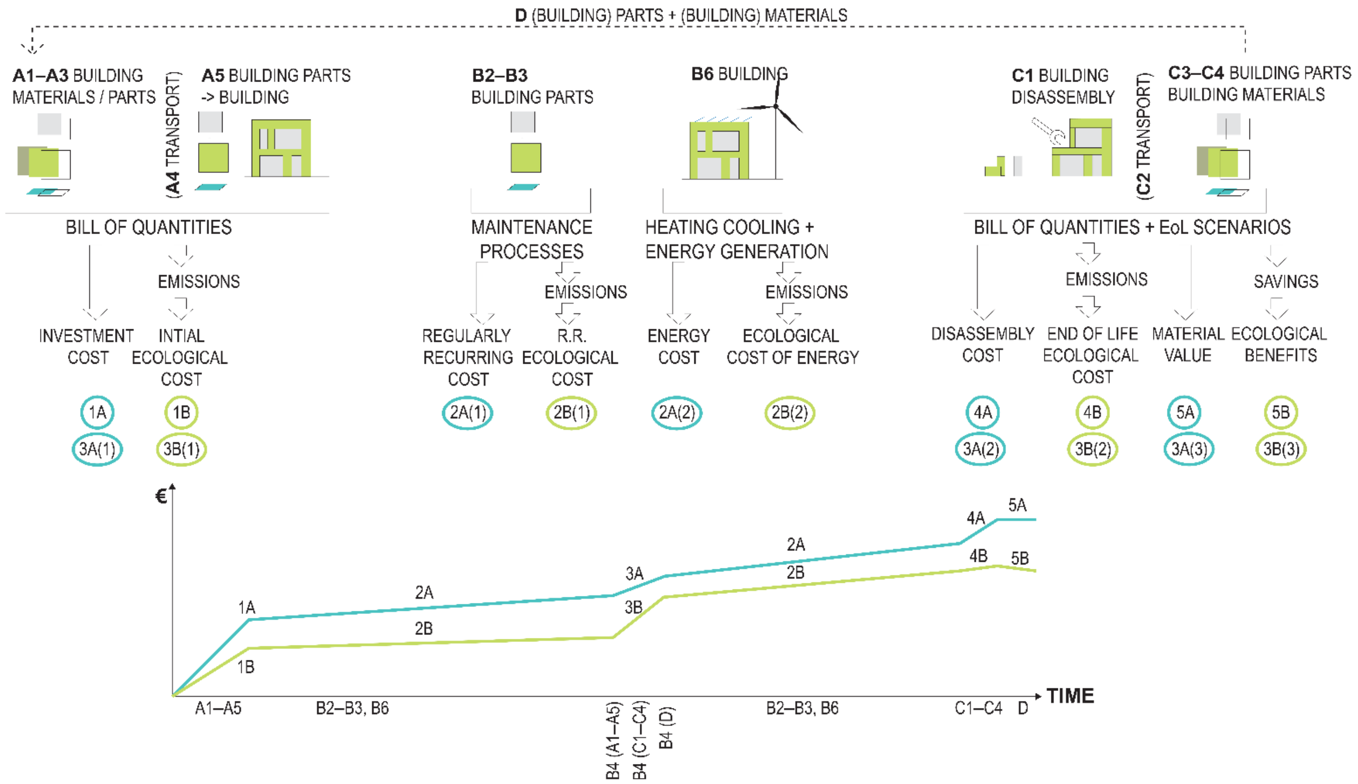


Figure 3. Visualization of fLCC and eLCC in a timeline showing the levels of aggregation (material, building part building) for cost and emissions data; numbering of life cycle phases according to EN 15978.

2.8.1. Monetary Valuation

In the case study, we account for environmental impacts in terms of their actual or potential internalized cost, as this yields an easily comprehensible picture. In that sense, this case study is an extension of our investigation into monetary valuation as a weighting method [13], now including phase B6, the building's mechanical systems, and more closely aligning calculations according to the framework developed in [9]. The risk of this approach is that it might suggest that environmental damage can be fully compensated for in monetary terms. Therefore, we propose representing environmental life cycle cost (eLCC) separately from financial life cycle cost (fLCC) to avoid mixing the two cost values while maintaining a broader perspective than an individual investment scenario.

An important difference between LCA and LCC is the consideration of future costs. LCC uses discounting and price increase rates; this method is not applied in LCA. Using EC facilitates consideration of a temporal dimension in environmental evaluation by a quasi-dynamic approach, as is common practice in LCC. Because of the differing nature of EC, as they are not borne by individual investors but by society as a whole, discount rates and price change rates may differ from those pertaining to their financial counterparts.

Discounting of future emissions is often discouraged because of ethical concerns, as doing so values future emissions differently than present emissions, suggesting intergenerational inequality [43]. However, discounting can be justified for several reasons. For instance, it can account for a changing effect of emissions that may result from changing concentrations of pollutants in the atmosphere [43]. Additionally, if emissions are converted into external costs, these monetary values are subject to similar factors as financial costs. In light of this, both discounting and price changes should be considered for life cycle assessments. As Hoel et al. [44] point out, price increases counteract discounting and hence can be used to represent increasing resource scarcity or the changing financial value of damage costs. In economic valuation, discount rates are specific to the investor, based on time-preference assumptions and/or interest cost. To simplify calculations, discounting is, in most cases, assumed to be constant, although it is questionable for long-term considerations, as its effect is exponential [45]. As this is a highly controversial issue that has not been looked at in detail, we vary monetary valuation, price increase and discount rates to detect their influence on design recommendations.

We value environmental impacts at the high end of the spectrum found in the literature to obtain EC values (Table 2) to give more weight to eLCC compared to fLCC. A lower valuation set lowers the ratio between eLCC and fLCC but should not fundamentally change the quality of the comparison [13]. To isolate the effect of varying the temporal dimension (discount rates and price changes) we kept the EC values constant. In a second step, we varied the EC of the most influential emissions. However, in light of the considerable uncertainties pertaining to valuation of emissions, we consider monetary valuation more a weighting and comparison method than representative of actual cost magnitudes.

Table 2. Monetary valuation for environmental indicators used in this study for weighting and comparison purposes. EC, environmental cost; GWP, global warming potential; ODP, ozone depletion potential; AP, acidification potential; EP, eutrophication potential; ADPE, abiotic depletion potential (elements).

Indicator	**EC GWP [€/kg CO_2-eq.]**	**EC ODP [€/kg R11-eq.]**	**EC POCP [€/kg Ethen-eq.]**	**EC AP [€/kg SO_2-eq.]**	**EC EP [€/kg PO_4-eq.]**	**EC ADPE [€/kg Sb-eq.]**
Model	Damage costs; 0% pure time preference; equity weighting [1]	Damage costs [2]	Marginal prevention costs [3]	Damage costs [1]	Damage costs [4]	Restoration costs [5]
Value 2020	0.65€	90.91€	9.59€	14.71€	20.74€	17 232.63€
Variation	+30%; −70%	N/A	N/A	±30%	N/A	±30%

[1] [46,47]; [2] [48]; [3] [49]; [4] [50]; [5] [51].

Previous use cases [13,14] show a strong dependency of the EC of building materials (CG 300, structure and finishes) on two indicators: GWP and ADPE. AP plays a visible albeit minor role. EP, OPD and POCP contribute only marginally to total EC. This case study extends this investigation to a range of material and energy supply alternatives, varying cost for the three indicators, GWP, AP and ADPE.

We investigated this observation on background data level by converting all datasets of Oekobaudat 2020-II [26] into environmental costs using minimum and maximum values from [13]. Table 3 shows the summarized results, whereas the corresponding box plots show the data in more detail (Appendix C, Figures A1–A4). For all Oekobaudat datasets applicable for elements of CG 300, the average contribution of GWP is 73% for life cycle phases A1–A3; followed by AP, with 12% and 14%; and ADPE with 8% or 11%. This underlines the fact that GWP is the dominant indicator for building materials. For the building's MEP systems (CG 400), the weight shifts towards ADPE. The most likely reason for this is the prominence of plastics and metals in MEP systems, materials with a high resource depletion potential. However, the large data gaps in CG 400 make these purely statistically derived numbers less certain. For the data for operational non-renewable energy use, GWP clearly dominates EC, with up to 97%. Although GWP, together with AP, is the decisive factor for renewable operational energy use, the resulting ECs are only a fraction of the ECs of non-renewable energy supply.

Table 3. Weighting of indicators according to minimum and maximum EC (Oekobaudat 2020-II [26]; modules A1–A3) * EC for renewables lie between 0.0002€ and 0.05€; for non-renewables, ECs are between 0.003€ and 0.40€.

	CG 300 Materials for Structure and Finishes	**CG 400 Materials for MEP Systems**	**Phase B6, Operational Energy Use Fossil**	**Phase B6, Operational Energy Use Renewable ***
Indicators causing largest share of ecological cost	GWP AP ADPE	GWP ADPE AP	GWP	GWP AP
Average contribution indicator to total EC (min valuation)	73% 14% 8%	58% 28% 12%	91%	47% 40%
Average contribution indicator to total EC (max valuation)	73% 12% 11%	63% 33% 4%	97%	66% 22%

Given the extensive discussions on carbon budgets, carbon tax and global warming mitigation and the strongly differing monetary values for carbon emissions, establishing a detailed top-down budget for each environmental indicator and a consensus on external cost seems unlikely in the near future. Hence, the case study varies the three most relevant indicators (GWP, AP and ADPE) to investigate whether this has an impact on the ranking of projects (Section 3.3).

2.8.2. Temporal Parameters

To account for the change in the value of money over time, cost is calculated as net present cost (NPC) per the following formula [37,52]:

$$X_{NPC} = \sum_{n=1}^{T} \frac{Cn}{(1+d)^n} = \sum_{n=1}^{T} \frac{C(1+p)^n}{(1+d)^n}$$

where X_{NPC} is net present cost, n = number of years between the base date and the occurrence of the cost, T = study period, d = expected real discount rate per annum, p = expected real price change per annum, Cn = cost in year n, and C = cost in the base year.

To deal with uncertainties regarding future scenarios and to show whether and how the temporal dimension informs and influences results, we conducted a scenario analysis with varying price increase and discount rates (Table 4).

Table 4. Values for discounting and price increase used in the scenario analysis; standard scenario values are shown, with variation range in brackets. fLCC, financial LCC (market price); eLCC, environmental LCC.

	Discount Rate	Price Increase
fLCC construction	3% (±1.5%)	2% (±1%)
fLCC services		2% (±1%)
fLCC energy		5% (±2%)
eLCC	0% (±1.5%)	5% (±2%)

Standard values for economic factors are taken from the BNB [37] and/or DGNB [36] framework. As the long-term uncertainty in energy prices and environmental impacts is potentially high, we applied a greater variation to these values than to market prices for construction and services. For environmental cost, current practice applies no discounting, i.e., a 0% discount rate. For potential price increases in damage and/or prevention costs, we chose the same rates as for energy prices. This is not customary in LCA, but it follows the logic of converting emissions into costs.

To combine the standard, minimum and maximum values, three alternative scenarios were considered: Scenario (1), standard, combines all standard values. In scenario (2), high time preference (high TP), present cost and emissions have a higher value than future cost and emissions, i.e., discount rates for both environmental and market costs are set to their maximum, whereas price increases are set to their minimum rates. In economic terms (fLCC), this means it would be preferable to save investment costs at present rather than in the future. This favors a building solution with low investment cost but high maintenance costs or a high exchange rate of materials and building parts. In environmental terms (LCA), high TP entails avoiding present emissions, even if this causes higher emissions in the future. Scenario (3), low TP, is the contrasting scenario to scenario (2). In this scenario, discount rates are set to their minimum, whereas price increases are set to their maximum rates. In economic terms (LCC), this scenario favors investment now over later investments. For a building, the low-TP scenario would suggest opting for a solution with high investment costs but low maintenance costs or a slow exchange rate of materials and building parts. In environmental terms (eLCC), this scenario encourages emitting now to save emissions later, e.g., employing an MEP system whose production is emission-intensive, but which saves emissions in the use phase.

To predict future emissions in building operation, we used a dynamic dataset to account for the development of the electricity mix. As there is an increasing share of renewable sources in the German electricity mix, as is the case for all countries with emission reduction targets related to the Paris agreement, emissions from electricity generation are changing. Therefore, CO_2 emissions can be expected to decrease gradually. To take this into account, we used the scenarios from the database Oekobaudat [26] for the years 2020, 2030, 2040 and 2050 to extrapolate the future cost of emissions. In effect, this leads to an annual decrease in EC of 1,6%. We coupled this with the above discount and price increase rates. This is the only dataset in Oekobaudat allowing for a dynamic approach, whereas all other (aggregated) datasets would require remodeling of all background processes.

To account for the differing approaches regarding phase D (Section 2.2), we show both results with and without this phase. We conducted the steps of the evaluation process with initial homogenous variations of the project (e.g., wood structure with wood exterior walls and bio-based insulation materials) and derived hybrid solutions from the results using favorable combinations, e.g., a reinforced concrete structure with non-load-bearing wood exterior walls. We do not describe this process in detail but include the developed solutions in the results.

3. Results

We describe the results in the standard scenario (Table 4), followed by the scenario analyses: first, the variation in temporal parameters and, second, the variation in monetary valuation.

3.1. Results: Standard Scenario

In this section, we present the results for the LCA and LCC of selected variations in the case study for the standard scenario. Results for all variations are shown in Appendix B.

3.1.1. Structure and Finishes (CG 300)

The diagram showing eLCC per fLCC (Figure 4) reveals that the fLCCs are comparatively close to each other for all variations, with the exception of the two solutions with an exterior curtain wall (CW). At the same time, the eLCCs vary greatly, with a small cluster of eLCCs around 50% of fLCCs.

Figure 4. Representation of fLCC (financial life cycle cost) per eLCC (environmental life cycle cost), including life cycle phase D, for CG 300 (structure and finishes) of all solutions. Solutions marked in colours were chosen for further analysis.

From these results, we selected five variations for representation in timelines, three of which contain a reinforced concrete structure and two of which contain a wood structure (Figure 1, Table A1). Each of these variations yields an extreme in at least one scenario: they result in give the lowest fLCC (RCC 03), highest fLCC (RCC 06), lowest eLCC (RCC 05) and highest eLCC (Wood 05). We added one solution (Wood 04) because experience with standard LCA calculations has shown that a wood structure with a ventilated façade is a recommended solution based on LCA results. Cumulated cost results for all variations can be found in Table A3 in Appendix B.

Figure 5 shows the development of the fLCC and the eLCC throughout the 50-year study period. The fLCC curves of the wood and concrete options converge, mainly due to the frequent exchange of carpet (every 10 years) and EIFS system (after 40 years). The building with a curtain wall displays the highest fLCC, acerbated by replacement of the curtain wall after 30 years.

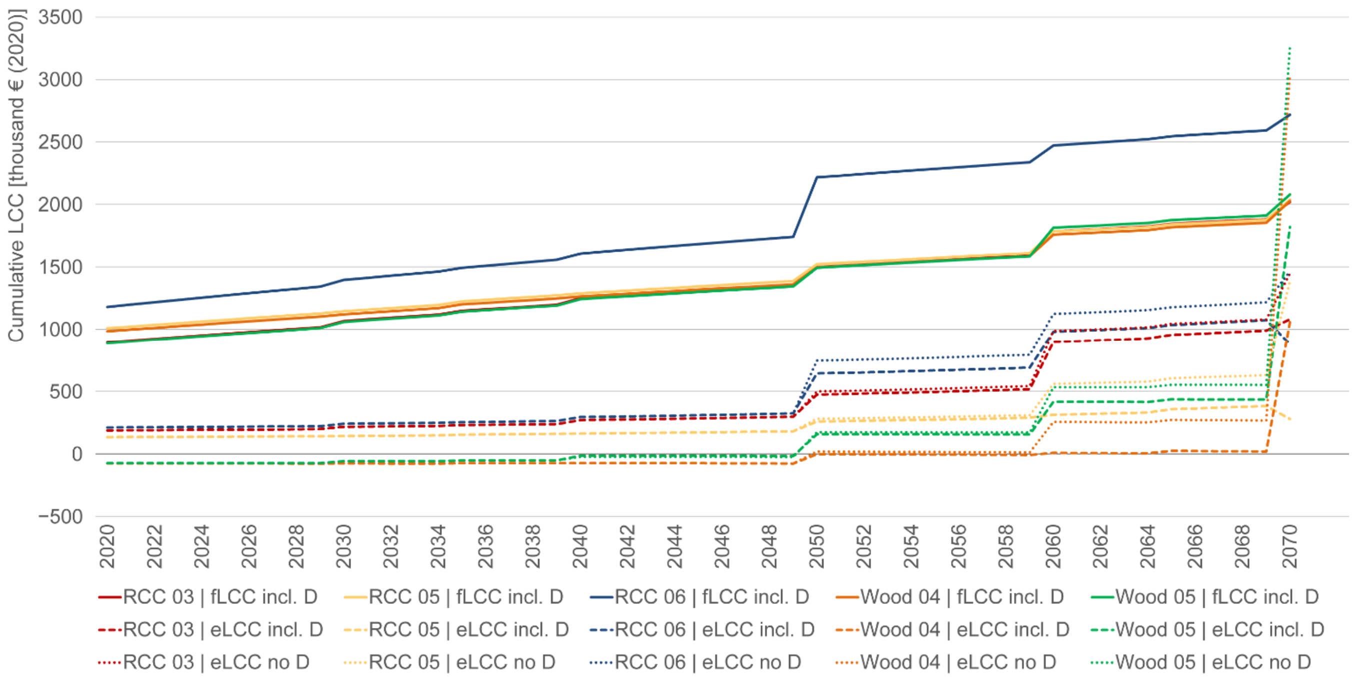


Figure 5. Timeline (present value, cumulative) of the fLCC (continuous lines) and eLCC, including phase D (dashed line) and excluding phase D (dotted line), of the building's structure and finishes (CG 300) in the standard scenario.

We see a striking effect of the price increase in EC on the significance of the end-of-life phases of the different buildings. In the standard end-of-life scenario for wood or other renewable materials, emissions from incineration for energy generation are accounted for in phase C3. Phase D in turn shows a credit for energy generation from renewables. This leads to the eLCC of the wood structures exceeding their fLCC if phase D is not accounted for and to their eLCC being higher than the eLCC of the concrete structures, even if phase D is included.

3.1.2. MEP Systems and Operational Phase (CG 400 + B6)

The diagram showing eLCC per fLCC (Figure 6) reveals that for CG 400 + B6, the fLCCs are closer together than the eLCCs for all variations. The difference between eLCCs is greater than for CG 300, and the absolute values exceed the eLCC of CG 300 (Figure 4).

The scenario analysis considers three different energy generation options (Figure 1, Table A2), two renewable energy sources (renewable district heat, MEP 03, and groundwater heat pump, MEP 01) and a non-renewable energy source (gas, MEP 02), the latter with and without PV (MEP 02A). As we recognized that the PV system causes significant amounts of EC in phases A1 to A3 because of its resource depletion potential, we included an option without PV to determine whether emissions savings would offset these costs in the operational phase. These variations yield the extremes: the lowest and highest eLCC and the lowest and highest fLCC. Notably, MEP 02A displays both the highest fLCC and the highest eLCC.

Considering that the same monetary valuation and framework as for the CG 300 investigation applies to CG 400 + B6, the most significant difference between the two building subsystems is the fact that all but one variation display higher eLCCs over their lifetime than fLCCs, even if phase D is included in the calculation (Figure 7). This is due to the high EC caused by the burning of fossil fuels which is visible by the comparatively steep slope of the timelines and is even present in the renewable heat supply solutions due to the electricity mix. Moreover, the ratio of environmental cost of parts of the MEP systems (e.g., PV cells, copper cables) to the financial cost is higher than for building materials (CG 300).

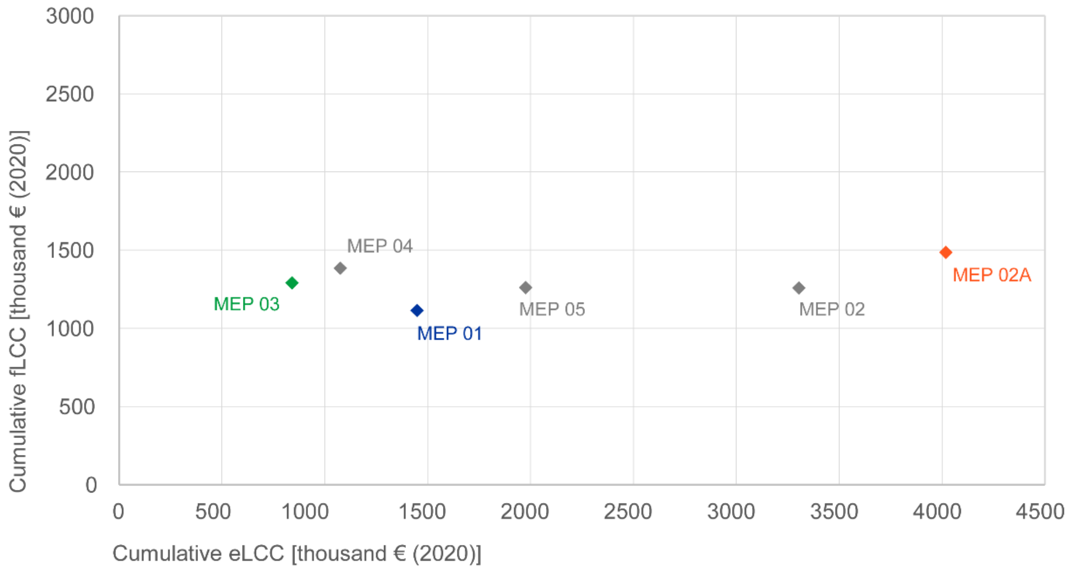


Figure 6. Representation of fLCC (financial life cycle cost) per eLCC (environmental life cycle cost), including life cycle phase D, of the building's HVAC and MEP systems (CG 400) and operational energy use (B6) of all solutions. Solutions marked in colours were chosen for further analysis.

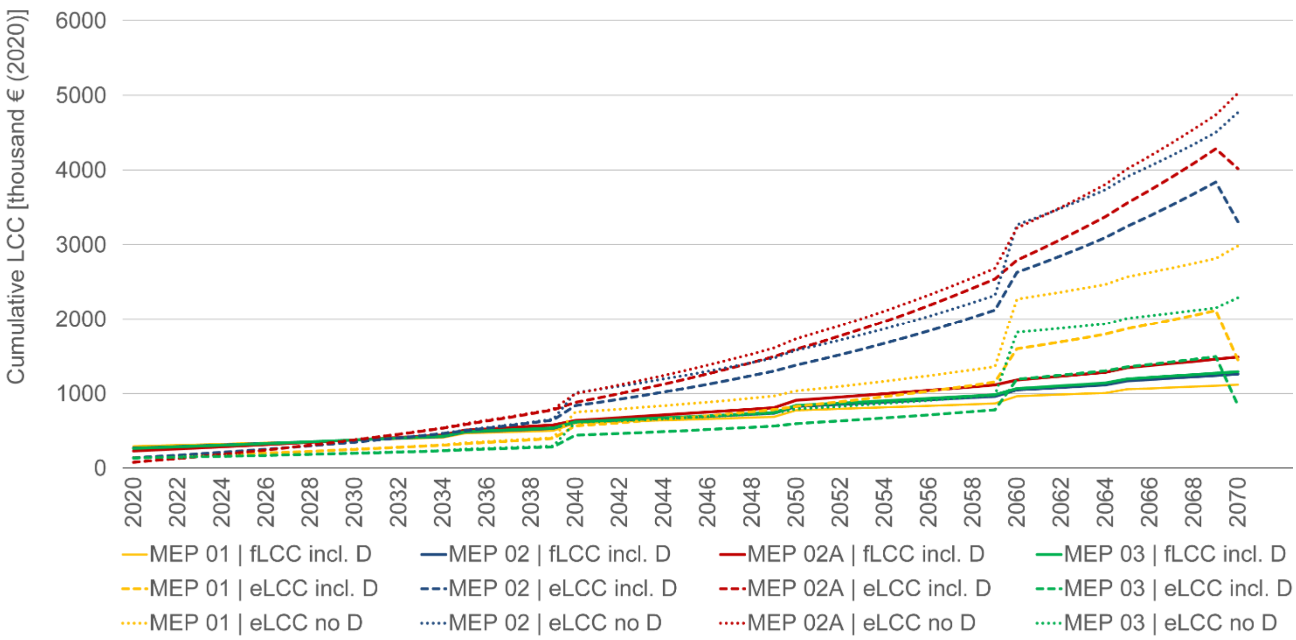


Figure 7. Timeline (present value, cumulative) of the fLCC (continuous line) and eLCC, including phase D (dashed line) and excluding phase D (dotted line), of the building's HVAC and MEP systems (CG 400) and operational energy use (B6) in the standard scenario.

Here, the inclusion or exclusion of phase D also has a significant impact, as the recycling potential of the materials contained in MEP systems (first and foremost metals) is high. As several MEP elements have a relatively short reference service life (RSL) by standard definitions, e.g., PV cellsare replaced every 20 years [53], this also heavily influences phase B4. The timeline representation makes this visible with a steeper or flatter slope at every exchange point of an element, depending on whether phase D is excluded or included. It is also clear that under standard framework conditions, the PV systems' EC are offset by their emissions savings in relation to the standard electricity mix, despite the gradual improvement in electricity mix and regardless of whether phase D is included or not.

3.2. Temporal Dimension: Scenario Analysis

We varied the temporal dimensions (discount rates and price changes) according to the scenarios in Table 4 to answer the question whether and how introducing the temporal dimension in LCA influences results.

3.2.1. Structure and Finishes (CG 300)

In addition to the expected result that the overall cumulative costs (present value) increase with lower time preference and higher price increase rates (Figure 8), the scenarios change the ranking of the different variations according to their total cost (eLCC + fLCC). We observe that adding eLCC and fLCC provides a better direction towards solutions with lower environmental cost than considering eco-efficiency. Eco-efficiency is seemingly favorable for options with high fLCC, implying that higher financial investment allows for higher emissions. The recommended solution based on fLCC is only identical to the recommended solution based on total cost, if it is identical to the solution with the lowest eLCC (RCC 05 in the low-TP scenario without D). In all other cases, adding eLCC to fLCC changes the recommended solution. However, the scenario choice influences the ranking according to fLCC, as well as according to total cost (with or without D). This implies that a potential recommendation to a client strongly depends on the scenario.

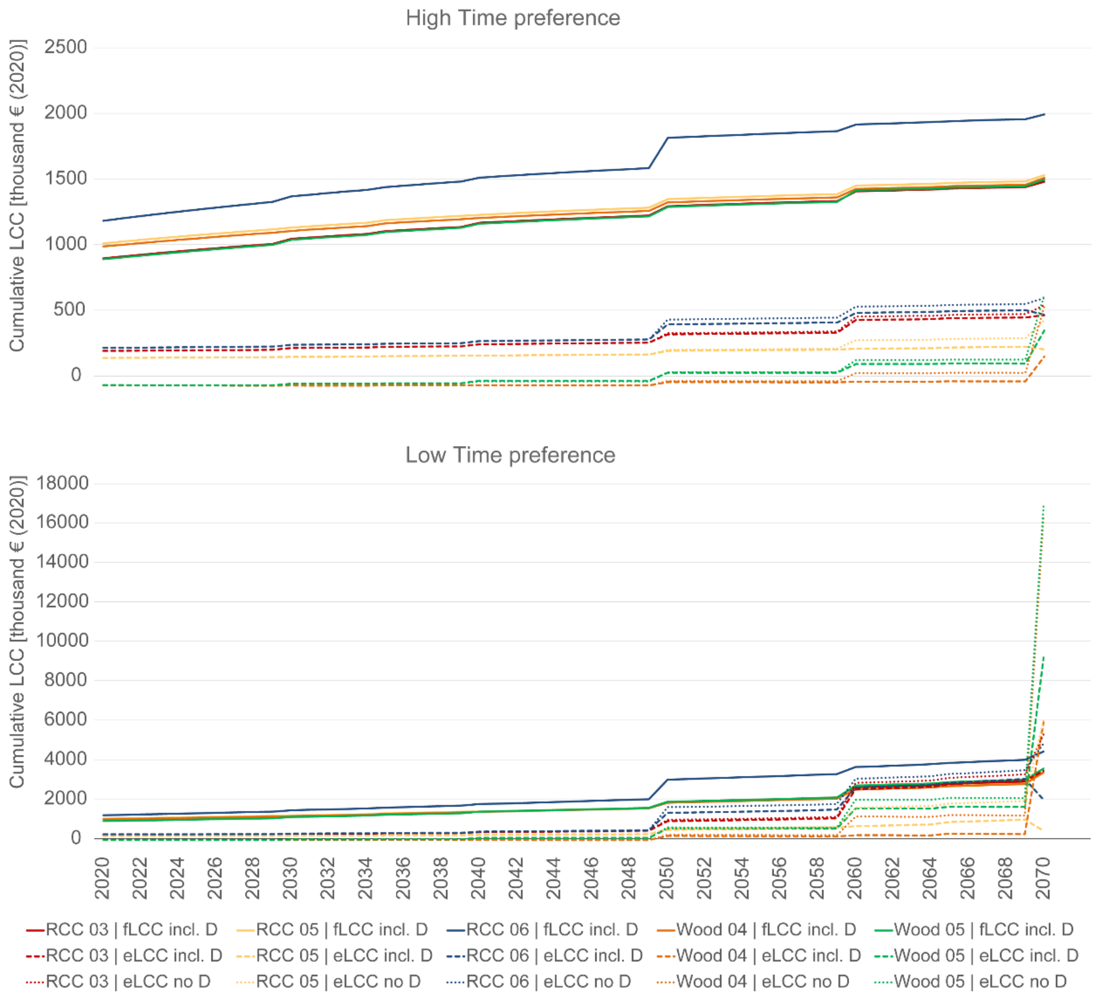


Figure 8. Comparison of the timelines for the different scenarios for the building's structure and finishes. Above: high-time-preference scenario (2); below: low-time-preference scenario (3).

Overall, the choice of time preference scenario has a greater impact on eLCC than on fLCC, as the end-of-life phases play a more significant role in environmental than in economic considerations. Comparing all building variations in all scenarios regarding their total cost (Tables A3–A5 in Appendix B), variations with a wood structure outperform those with a reinforced concrete structure only for the scenario with high TP if phase D is included. Hybrid variation RCC 05 ranks first in the standard and low-TP scenario if phase D is included; it still ranks high (rank 3 of 13) in the high-TP scenario. If phase D is excluded, the recommendation stays the same for the standard and low-TP scenario but changes for the high-TP scenario.

3.2.2. MEP Systems and Building Operation (CG 400 + B6)

In contrast to the building's structure and finishes, the choice of temporal parameters changes the eco-efficiency and total cost in absolute terms but does not change the ranking of the different solutions (Figure 9). This is true for all solutions considered, not just the four solutions shown in Figure 9 (Tables A6–A8 in Appendix B). This observation can be explained by the fact that the operational phase with regularly recurring costs and emissions is the decisive factor for this investigation, unlike the end-of-life phase, which occurs only at one point in the future, when discounting and price increases have their full effect.

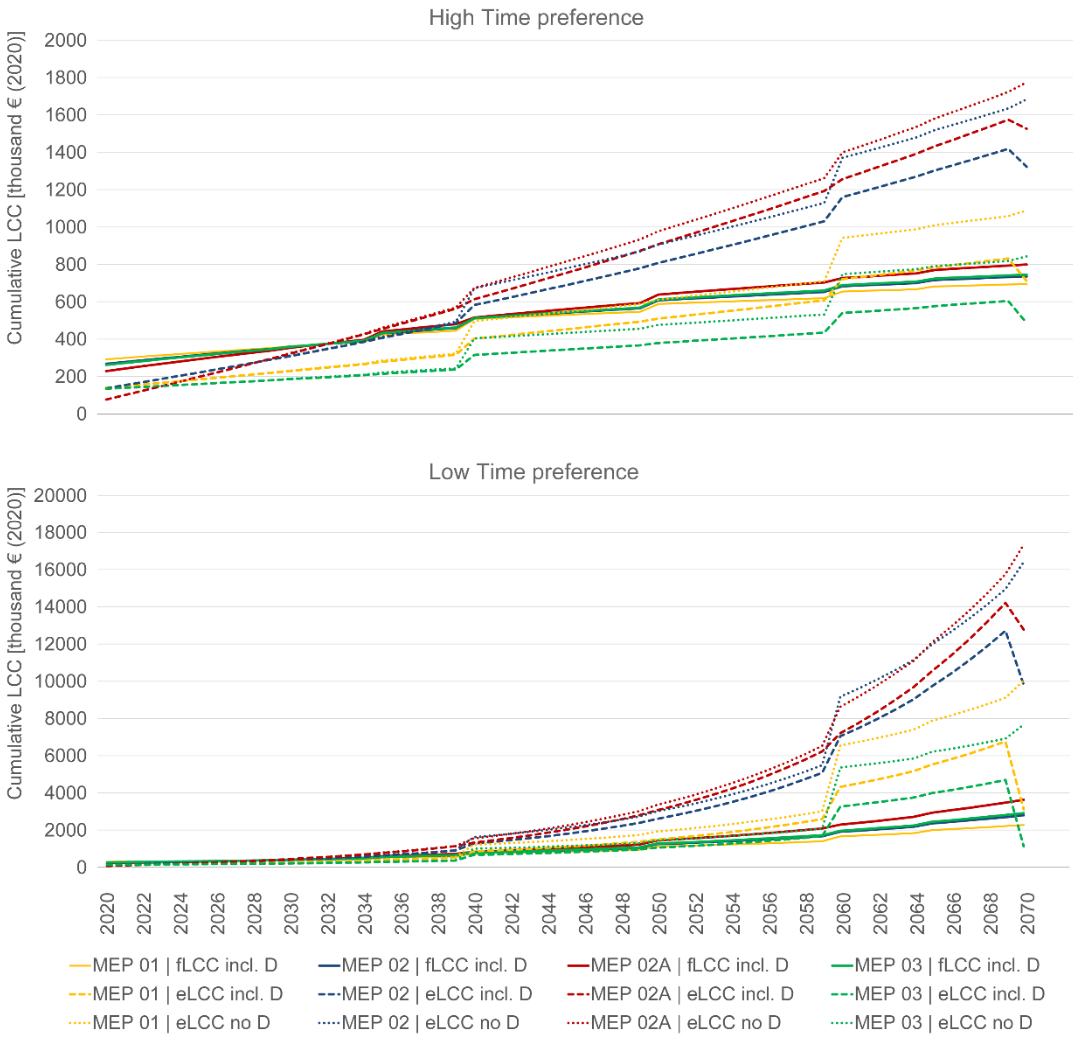


Figure 9. Comparison of the timelines for the different scenarios for the building's MEP systems and operation. Above: high-time-preference scenario (2); below: low-time-preference scenario (3).

As a second notable difference between the two subsystems, CG 300 and CG 400 + B6, we observe that despite the same monetary valuation system, the eLCCs of the MEP systems and phase B6 exceed their fLCCs in all scenarios except for MEP 03 if phase D is included. This occurs quickly (within 9 to 14 years) for MEP 02 and MEP 02A and later in the lifetime of the building (20 years) for MEP 01. In contrast, for the building's structure and finishes, the eLCCs stay below the fLCCs for most of the building's lifetime and only exceed fLCC for the low-TP scenario toward the end of the study period. In the standard scenario, this occurs only for the wood buildings if phase D is excluded (Figure 5).

3.3. Implications of Monetary Valuation

3.3.1. Weighting Environmental Impact Indicators

In terms of the relevant indicators and the ratio between life cycle ecological costs and life cycle financial costs, major differences appear between (Table 5):

- the building's structural and finish materials (CG 300);
- MEP systems (HVAC systems, electrical systems and sanitary installations: CG 400); and
- operational energy use (life cycle phase B6).

Table 5. Weighting of indicators resulting from life cycle environmental cost and comparison between life cycle environmental and life cycle market cost (NPC, standard scenario).

	CG 300 Structural and Finish Materials	**CG 400 Building Services (MEP Systems)**	**Phase B6 Building Operation (Energy Use)**
Indicators causing largest amount of eLCC	GWP ADPE	ADPE GWP	GWP (93–98% for non-renewables)
Ratio eLCC/fLCC (net present cost)	no D: 54% to 157% incl. D: 14% to 88%	no D: 156% to 237% incl. D: −11% to 33%	97% to 568%

For CG 300, global warming potential (GWP) is responsible for the largest share of eLCC, followed by the cost of resource depletion (ADPE). The use case variations show that external costs amount to 14% to 157% of the building's life cycle cost, depending on the materials used and, on the question, whether life cycle phase D (benefits and loads outside of the system boundary) is included in the calculations.

Abiotic resource depletion of elements (ADPE) is dominant for the eLCC of CG 400, followed by the eLCC of GWP. This is caused by the use of metals, which show values for ADPE higher than those of other materials by a factor of up to 10^6. It is one of the particularities of ADPE that single materials cause the largest share of environmental costs, disproportionally to their share in the overall building mass. Compared to the fLCC of the building's MEP systems, eLCC amounts to −11% to 237%, even more strongly depending on the inclusion or exclusion of phase D than for CG 300. Note that the negative values for fLCC reflect a high ADPE credit for recycling metals.

A proportion of 93% to 98% of the eLCC of building operation are caused by GWP if non-renewable or partially non-renewable energy sources are used. In the case of bio-based energy sources, GWP's share ranges from 51% to 71%, followed by acidification potential (AP) (up to 31%). Overall, environmental costs amount to up to 568% of the life cycle operational costs, strongly depending on the share of non-renewable energy sources used. As many countries are starting to tax CO_2 emissions associated with building operation, this is important information for stakeholders. By decarbonizing the energy supply system of the building at a comparatively low cost premium, environmental costs of building operation can be reduced to a minimum, as confirmed by previous studies [54].

3.3.2. Varying Monetary Valuation

We varied monetary valuation values, as shown in Table 2, to investigate how the different values affect the eco-efficiency ratio and whether or not this influences the ranking of options if eLCCs were added to fLCCs. We looked at the ranking of options based on fLCC, eLCC, eco-efficiency and total cost (fLCC + eLCC), each with and without phase D. All results are provided in Supplementary Data S1. Generally, within one time preference scenario, the recommendation based on fLCC stays the same, as monetary valuation does not influence the results.

For CG 300, varying monetary valuation changes recommendations based on fLCC + eLCC only in one case. Minimum valuation and high time preference excluding phase D recommends RCC 03 rather than RCC 05, as the difference in eLCC does not make up for the difference in fLCC. In other words, the monetary valuation model has almost no influence on the ranking of results compared to the considerable influence of time preference scenarios.

For CG 400, recommendations based on fLCC + eLCC remain unchanged between medium and high monetary valuation. At low valuation, recommendations shift towards the solutions with lower fLCC (MEP 01), although MEP 03 remains the solution with the lowest eLCC.

At minimum valuation and low time preference, we observe that the eLCC results in negative values if phase D is included, implying a savings of eLCC because of the high price increase in environmental costs in 50 years.

4. Discussion

4.1. Gaps and Limitations of the Use Case

When applying the framework, several gaps that have not been previously addressed provide opportunities for further research. First, the sensitivity analysis conducted for temporal parameters and monetary values could incorporate further aspects of life cycle uncertainty. Previous studies have addressed single parameters in LCA and/or LCC, such as service lives of elements [55], building lifespan [56,57], material data [58] or design vagueness [20,59]. Experience from these studies can inform a more global sensitivity study on influential parameters. Second, the data gaps identified in [9] also became apparent in this study. The database used in this study, Oekobaudat, provides only limited data on project-specific life cycle phases, such as transport, construction and disassembly (A4, A5, C1 and C2). Data on environmental impacts and cost of MEP systems is sparse and not well-structured; for example, functional units (e.g., kg of ducts) do not lend themselves to early design exploration. Available as-built information about the case study made it possible to consider these data, but further work is required to enable consideration of embedded impacts of MEP systems in a real-life design process. Data gaps in LCC pertain to the end-of-life phases, and cost for disassembly vs. conventional demolition processes is lacking, as well as disposal, reuse, recycling cost or value. For this study, we attached end-of-life costs to building parts and surfaces in order to account for replacement processes. Although we used the same costs for end-of-life processes—at the risk of overestimating these costs, as they are tantamount to an elaborate disassembly process—these costs only play a minor role in the fLCC calculations. However, with increasing cost of landfills and decreasing resource availability, end-of-life costs could contribute significantly to fLCC. In summary, establishing a sound database for both LCA and LCC in parallel would be beneficial for the accuracy and true harmonization of the two methods. This database should close the mentioned data gaps and, ideally, contain information about building parts with different material configurations and building operation. Third, we excluded the mutual influence of MEP systems, energy standard and construction materials to detect differences in the scenario analysis. However, a more extensive variant study could reveal further dependencies and, ideally, win–win situations.

The case study is representative of small office buildings in Germany. The small size and homogenous use profile limited complexity to enable many variations in a manual process. However, the framework can be used on larger-scale buildings and mixed-use developments requiring digital methods to handle the complexity of interdependencies.

4.2. Quasi-Dynamic LCA

The quasi-dynamic approach provides a method to introduce a time horizon into LCA without the necessity of recalculating all underlying data. It reveals a striking influence of the choice of temporal parameters on life cycle results and related recommendations. The low-time-preference scenario implies that future costs and emissions weigh more heavily than present costs and emissions, whereas the high-time-preference scenario focuses on saving costs and emissions now rather than in the future. Both scenarios are worth considering. Given the sense of urgency caused by signs of increasing environmental and social problems resulting from global warming, the high-time-preference scenario can be justified by the argument that if we manage to avoid enough emissions and the resulting serious environmental and economic consequences now, saving emissions in the future could be regarded as less important. Following this logic, deferring emissions should be prioritized, e.g., using wood as a construction material and thereby using buildings as a long-term carbon sink [60]. Under the low-time-preference scenario, the opposite would be the case, resulting in a contradictory recommendation: it is better to cause higher emissions now to save emissions later, while these same (present) emissions might tip the scale towards more serious environmental problems.

In all scenarios, the inclusion or exclusion of end-of-life credits has a significant impact, especially on options with large amounts of wood or metals. This is in line with results from the literature suggesting that wood and steel options are more sensitive towards changes in discount rates due to significant credits in the end-of-life phases [33].

Introducing the time horizon by a quasi-dynamic approach into LCA calculation poses the challenge that emissions evaluation of future processes is based on emissions of current processes. It should be further developed to a truly dynamic method, adding scenarios for future developments in background systems, such as the electricity mix, technological advancements [17] and the time horizon for impacts [15]. In this study, we included a dynamic factor for the electricity mix, as scenarios for the German electricity mix exist. Transferring this scenario to manufacturing processes would require an overall building sector scenario, information about the share of electricity used in manufacturing processes and a dynamic recalculation of environmental data for manufacturing building materials. Such a future scenario might also question the assumption that the same materials and MEP systems, rather than more advanced solutions, replace current technologies at the end of their service life.

Furthermore, the quasi-dynamic approach shows how the length of the study period could be highly significant for decisions made in the design process. The length of the study period represents the potential lifetime of the building, which is subject to a multitude of factors and can therefore vary greatly. The representation of the life cycle in a timeline enables LCA and LCC consultants to discuss the building's life cycle with regard to a client's investment horizon, providing insights into credits and liabilities (both in financial and environmental terms) for a future owner and/or user of the building.

4.3. Monetary Weighting

Despite providing valuable insight into the weighting of different environmental indicators and the ratio between life cycle (market) costs and environmental costs, monetizing LCA results bears the danger of underestimating damage to ecosystems and society. Moreover, it runs the risk of suggesting that paying a fee can avoid or mitigate environmental damage. Communication to stakeholders should therefore clearly state that environmental costs are theoretical costs used to summarize the results of ecological calculations, which are likely to be incomplete. For example, building LCA in Germany disregards toxicity because of the lack of agreed-upon and methodologically robust indicators. Additionally, the underlying weighting system and the contribution of single indicators need to be transparent. In this way, monetary valuation identifies the main drivers of EC of buildings, providing guidance towards high emission reduction potentials.

The monetary weighting system used in this study is based on previous work by the authors [13], using the maximum values found in the literature. Including other midpoint impacts beyond GWP in monetary valuation allows for a broader picture than monetizing carbon emissions only. However, it also reveals that GWP largely determines the EC of building materials. Hence, the scenario choices have the largest influence on those building variations with a large share of carbon emissions occurring in the future, i.e., with a large share of renewable materials. How these are evaluated depends, in turn, on both the end-of-life scenarios for these materials and, more importantly, the biogenic carbon accounting method used. As Oekobaudat accounts for biogenic carbon storage in phase A1, for the release of carbon in phase C3 (incineration for energy generation) and for credits due to energy generation in phase D, carbon storage is equivalent to deferring emissions. As Resch et al. [15] point out, a dynamic approach to GWP provides further insight into the effect of delaying emissions. It is the subject of future research to investigate further scenarios with dynamic carbon accounting, as described by Hoxha et al. [61] using the Eco^2 framework to couple the scenarios with economic considerations.

The case study combines MEP systems and building operation (phase B6), as these are mutually dependent. The different solutions regarding the energy generation system show that embedded emissions of the MEP systems are dwarfed by the emissions in phase B6 during the 50-year study period. A particularity of MEP systems in comparison to the building's structure and finishes is the predominance of resource depletion. For the PV system, this leads to the EC of phase A1–A3 exceeding the investment cost of the system. However, emissions-free electricity offsets this EC in comparison to the general electricity mix. Further investigation into the magnitude of the EC of resource depletion is necessary to gain a better understanding of this process.

Lastly, we asked the question of whether adding monetary values for environmental impacts can tip the scale towards lower emission solutions if these prove to have higher life cycle costs than solutions with higher emissions. Overall, we found that changing monetary valuation has a lesser influence on results based on total cost than time preference does. Given the high uncertainty in monetary valuation, this encourages the use of monetary valuation, as in most cases, adding eLCC to fLCC provides leverage towards emission-saving solutions. Additionally, for CG 300 in the high-time-preference scenarios, the solution with the lowest eLCC is also the solution with lowest fLCC, representing a win–win situation. Adding eLCC to fLCC in this case only increases the difference between solutions.

For the building's MEP systems and operational energy use, the preferred solution is the one with the lowest eLCC if medium or high monetary valuation is used. For low valuation, this solution is only preferred at high TP. We conclude that medium or high valuation of environmental impacts gives enough weight to emissions to provide leverage towards lower emissions. Moreover, adding eLCC to fLCC appears to be a valuable strategy for identifying solutions that minimize both fLCC and eLCC.

5. Conclusions

Calculating LCA and LCC in parallel requires extensive background data, as well as expertise and time, which is often a sparse resource in regular design processes. Therefore, we developed an Eco^2 framework in a previous study to structure the integrated process. This second part of the study tests the Eco^2 framework in a fictitious building design process based on a real-life case study of a small-scale office building.

Collecting the background data for the case study closes some typical LCA and LCC data gaps and lays the groundwork for a common environmental–economic database. It also reveals that different types of data need to be associated with various aggregation levels of building materials, building parts or the whole building. Extending this project-specific data collection to a more widely usable database enables a design supported by Eco^2.

Considering discounting and price changes in LCA and thus adding a temporal dimension is not a standard procedure in current LCA calculations, which use a static approach and show total emissions, at best, by life cycle phase and at worst as a total sum. Varying the temporal parameters assists practitioners in discussing time preference not only in economic but also environmental terms. The case study shows that the choice of time preference scenario decisively influences potential recommendations regarding the building's structure and finishes but leaves recommendations regarding the MEP systems largely unchanged. This implies that time preference is less important for MEP systems than for building materials, as the choice of MEP systems, in effect, determines emissions in the operational phase, which recur regularly. For building materials with high emission values and credits in the end-of-life phases (e.g., wood and metals), varying the temporal parameters and including or excluding credits (phase D) has a great influence on environmental life cycle costs because these are incurred at one point in the distant future, when the exponential effect of temporal parameters is largest.

Applying different monetary values for emissions as a form of weighting of the environmental indicators and as a "counterweight" to economic results affects the total cost (environmental and financial life cycle cost, eLCC+fLCC). In the case study, adding eLCC to fLCC shifts recommendations from the solutions with the lowest fLCC to solutions with the lowest eLCC unless a very low valuation of emissions is used. It also reveals win–win solutions with both low fLCC and low eLCC.

The eLCC of MEP systems and energy use in operation tend to exceed the fLCC of MEP systems and energy use. This leads to the conclusion that this factor remains extremely influential for the overall life cycle performance of a building, even with an ambitious energy standard. It implies that the choice of MEP system is the decision with the most leverage in environmental terms without being economically disadvantageous. As GWP dominates the EC of building operation, this is in line with previous studies and policy recommendations identifying renewable energy systems as the most economically efficient emissions-saving strategy.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su14106025/s1.

Author Contributions: Conceptualization, methodology, formal analysis, investigation and data curation: P.S.-M.; writing—original draft preparation: P.S.-M.; writing—review and editing: W.L.; visualization: P.S.-M.; supervision: W.L.; funding acquisition: W.L. and P.S.-M. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Deutsche Forschungsgemeinschaft (German Research Foundation, DFG) under grant FOR2363 (project number 271444440).

Acknowledgments: We thank Ferdinand Tausendpfund GmbH for allowing us to use their office building as a case study, in particular for the valuable and detailed information about the building's MEP systems. Thank you to Anne Winkelkotte for her Master thesis work, which inspired part of this research, and to Tanja Stocker for her assistance in grouping Oekobaudat data. For their scientific input and valuable feedback, we sincerely thank Leander Schneider and Inger Andresen. Last but not least, we thank four anonymous reviewers for their valuable feedback.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

AP	acidification potential
ADPE	abiotic depletion potential of elements
BIM	building information modelling
BNB	Bewertungssystem nachhaltiges Bauen (building sustainability evaluation system)
DGNB	Deutsche Gesellschaft für nachhaltiges Bauen (German sustainable building council)
EC	environmental cost
eLCC	environmental life cycle cost
EP	eutrophication potential
fLCC	financial life cycle cost
GHG	greenhouse gas
GWP	global warming potential
HVAC	heating, ventilation, air conditioning
LCA	life cycle assessment
LCC	life cycle costing
MEP	mechanical, electrical, plumbing
NPC	net present cost
ODP	ozone depletion potential
POCP	photochemical ozone creation potential
PV	photovoltaic
RSL	reference service life
TP	time preference

Appendix A. Case Study Specifications

Table A1. Characteristics of the variations in the building's structure and finishes shown in the timelines. RCC: reinforced concrete; SL brick: sand–lime brick; EIFS: exterior insulation and finish system; EPS: expanded polystyrene; PVC polyvinyl chloride.

Variation Name	Structure	Ext. Wall Core	Ext. Wall Finish	Window Frames	Insulation Material Int. Floors	Floor Finish	Interior Load-Bearing Walls	Interior Non-Load-Bearing Walls
RCC 03	RCC	SL brick	EIFS (EPS)	PVC	EPS	carpet	masonry	metal stud drywall
RCC 05	RCC	Wood frame	Ventilated (alum. siding)	wood	wood fiber	wood parquet	masonry	wood stud drywall
RCC 06	RCC	Curtain wall (alu.)	Aluminum siding	(alum.)	EPS	carpet	masonry	metal stud drywall
Wood 04	Solid wood	Wood frame	Ventilated (alum. siding)	wood	wood fiber	wood parquet	solid wood	wood stud drywall
Wood 05	Solid wood	Wood frame	EIFS (wood fiber)	PVC	EPS	carpet	solid wood	metal stud drywall

Table A2. Characteristics of the variations in the building's energy supply system shown in the timelines.

Variation Name	Heating Supply	Cooling Supply	PV
MEP 01	Groundwater heat pump	Compression (electricity)	yes
MEP 02	Gas condensing boiler	Compression (electricity)	yes
MEP 02A	Gas condensing boiler	Compression (electricity)	no
MEP 03	Renewable district heat	Compression (electricity)	yes

Appendix B. Case Study Results: Medium Monetary Valuation

Table A3. Comparison of all variations in CG 300 (standard scenario) (1). The colors indicate the lowest (green) and highest values (red), gradation for the ranking in-between.

Variation	eLCC (No D)	eLCC (Incl. D)	fLCC	eLCC No D/fLCC	eLCC Incl. D/LCC
RCC 01	1,454,277€	1,067,346€	2,098,014€	69.3%	50.9%
RCC 01A	1,351,859€	1,026,404€	2,110,477€	64.1%	48.6%
RCC 02	1,328,615€	990,597€	2,044,960€	65.0%	48.4%
RCC 02A	1,283,670€	967,248€	2,049,106€	62.6%	47.2%
RCC 02B	1,398,825€	932,434€	2,068,703€	67.6%	45.1%
RCC 03	1,448,969€	1,080,746€	2,020,972€	71.7%	53.5%
RCC 04	1,450,918€	744,124€	2,059,883€	70.4%	36.1%
RCC 05	1,386,873€	279,927€	2,038,062€	68.0%	13.7%
RCC 06	1,465,022€	880,698€	2,717,295€	53.9%	32.4%
Wood 04	3,043,717€	1,058,493€	2,027,408€	150.1%	52.2%
Wood 04A	3,170,602€	1,408,453€	2,048,539€	154.8%	68.8%
Wood 05	3,266,101€	1,819,585€	2,079,617€	157.1%	87.5%
Wood 06	3,159,066€	1,283,054€	2,651,549€	119.1%	48.4%

Variation	fLCC + eLCC (No D)	fLCC + eLCC (Incl. D)	Ranking Based on fLCC	Ranking Based on fLCC + eLCC No D	Ranking Based on fLCC + eLCC Incl. D
RCC 01	3,552,291€	3,165,360€	10	8	9
RCC 01A	3,462,336€	3,136,881€	11	4	8
RCC 02	3,373,575€	3,035,557€	4	2	5
RCC 02A	3,332,777€	3,016,355€	6	1	4
RCC 02B	3,467,528€	3,001,137€	8	5	3
RCC 03	3,469,941€	3,101,718€	1	6	7
RCC 04	3,510,800€	2,804,007€	7	7	2
RCC 05	3,424,935€	2,317,989€	3	3	1
RCC 06	4,182,317€	3,597,993€	13	9	11
Wood 04	5,071,124€	3,085,900€	2	10	6
Wood 04A	5,219,141€	3,456,992€	5	11	10
Wood 05	5,345,719€	3,899,203€	9	12	12
Wood 06	5,810,615€	3,934,603€	12	13	13

Table A4. Comparison of all variations in CG 300 (high-time-preference scenario) (2). The colors indicate the lowest (green) and highest values (red), gradation for the ranking in-between.

Variation	eLCC (No D)	eLCC (Incl. D)	fLCC	eLCC No D/fLCC	eLCC Incl. D/LCC
RCC 01	542,878€	463,417€	1,543,833€	35.2%	30.0%
RCC 01A	522,332€	455,761€	1,552,990€	33.6%	29.3%
RCC 02	510,346€	440,888€	1,505,893€	33.9%	29.3%
RCC 02A	498,599€	433,668€	1,508,939€	33.0%	28.7%
RCC 02B	516,114€	419,739€	1,523,337€	33.9%	27.6%
RCC 03	537,319€	461,208€	1,479,057€	36.3%	31.2%
RCC 04	525,496€	387,226€	1,523,891€	34.5%	25.4%
RCC 05	422,631€	201,149€	1,528,473€	27.7%	13.2%
RCC 06	591,671€	464,252€	1,992,432€	29.7%	23.3%

Table A4. *Cont.*

Variation	eLCC (No D)	eLCC (Incl. D)	fLCC	eLCC No D/fLCC	eLCC Incl. D/LCC
Wood 04	526,262€	145,253€	1,507,964€	34.9%	9.6%
Wood 04A	513,725€	176,521€	1,498,082€	34.3%	11.8%
Wood 05	615,922€	344,207€	1,494,950€	41.2%	23.0%
Wood 06	631,454€	258,236€	1,950,873€	32.4%	13.2%
Variation	**fLCC + eLCC (No D)**	**fLCC + eLCC (Incl. D)**	**Ranking Based on fLCC**	**Ranking Based on fLCC + eLCC No D**	**Ranking Based on fLCC + eLCC Incl. D**
RCC 01	2,086,711€	2,007,250€	10	10	10
RCC 01A	2,075,321€	2,008,750€	11	9	11
RCC 02	2,016,239€	1,946,781€	4	4	9
RCC 02A	2,007,538€	1,942,607€	6	2	7
RCC 02B	2,039,451€	1,943,076€	7	7	8
RCC 03	2,016,376€	1,940,265€	1	5	6
RCC 04	2,049,387€	1,911,117€	8	8	5
RCC 05	1,951,104€	1,729,622€	9	1	3
RCC 06	2,584,102€	2,456,684€	13	13	13
Wood 04	2,034,226€	1,653,217€	5	6	1
Wood 04A	2,011,808€	1,674,603€	3	3	2
Wood 05	2,110,872€	1,839,157€	2	11	4
Wood 06	2,582,327€	2,209,109€	12	12	12

Table A5. Comparison of all variations in CG 300 (low-time-preference scenario) (3). The colors indicate the lowest (green) and highest values (red), gradation for the ranking in-between.

Variation	eLCC (No D)	eLCC (Incl. D)	fLCC	eLCC No D/fLCC	eLCC Incl. D/LCC
RCC 01	5,273,049€	3,325,161€	3,473,354€	152%	96%
RCC 01A	4,765,285€	3,116,764€	3,494,411€	136%	89%
RCC 02	4,693,824€	2,989,530€	3,376,265€	139%	89%
RCC 02A	4,497,741€	2,898,623€	3,383,270€	133%	86%
RCC 02B	5,122,728€	2,793,300€	3,416,381€	150%	82%
RCC 03	5,270,709€	3,426,129€	3,359,262€	157%	102%
RCC 04	5,466,532€	1,784,772€	3,381,828€	162%	53%
RCC 05	6,030,094€	389,459€	3,331,686€	181%	12%
RCC 06	4,820,728€	1,966,446€	4,408,017€	109%	45%
Wood 04	16,343,445€	5,900,299€	3,354,515€	487%	176%
Wood 04A	17,225,915€	7,963,048€	3,462,528€	497%	230%
Wood 05	16,886,119€	9,170,541€	3,546,134€	476%	259%
Wood 06	16,030,523€	6,352,276€	4,331,642€	370%	147%
Variation	**fLCC + eLCC (No D)**	**fLCC + eLCC (Incl. D)**	**Ranking Based on fLCC**	**Ranking Based on fLCC + eLCC No D**	**Ranking Based on fLCC + eLCC Incl. D**
RCC 01	8,746,403€	6,798,514€	9	6	9
RCC 01A	8,259,697€	6,611,175€	10	3	7
RCC 02	8,070,089€	6,365,795€	4	2	5
RCC 02A	7,881,011€	6,281,893€	6	1	4
RCC 02B	8,539,110€	6,209,681€	7	4	3
RCC 03	8,629,972€	6,785,391€	3	5	8

Table A5. *Cont.*

Variation	fLCC + eLCC (No D)	fLCC + eLCC (Incl. D)	Ranking Based on fLCC	Ranking Based on fLCC + eLCC No D	Ranking Based on fLCC + eLCC Incl. D
RCC 04	8,848,360€	5,166,600€	5	7	2
RCC 05	9,361,780€	3,721,145€	1	9	1
RCC 06	9,228,746€	6,374,463€	13	8	6
Wood 04	19,697,961€	9,254,814€	2	10	10
Wood 04A	20,688,443€	11,425,575€	8	13	12
Wood 05	20,432,253€	12,716,675€	11	12	13
Wood 06	20,362,165€	10,683,919€	12	11	11

Table A6. Comparison of all variations in CG 400 + B6 (standard scenario) (1). The colors indicate the lowest (green) and highest values (red), gradation for the ranking in-between.

Variation	eLCC (No D)	eLCC (Incl. D)	fLCC	eLCC No D/fLCC	eLCC Incl. D/LCC
MEP 01	2,981,472€	1,448,856€	1,115,159€	**267%**	**130%**
MEP 02	4,766,964€	3,303,755€	1,259,252€	**379%**	**262%**
MEP 02A	5,026,850€	4,018,056€	1,486,969€	**338%**	**270%**
MEP 03	2,288,667€	839,932€	1,291,476€	**177%**	**65%**
MEP 04	2,540,220€	1,074,498€	1,384,925€	183%	78%
MEP 05	3,441,577€	1,975,856€	1,259,789€	273%	157%
Variation	**fLCC + eLCC (No D)**	**fLCC + eLCC (Incl. D)**	**Ranking Based on fLCC**	**Ranking Based on fLCC + eLCC No D**	**Ranking Based on fLCC + eLCC Incl D**
MEP 01	4,096,632€	2,564,015€	1	3	3
MEP 02	6,026,216€	4,563,007€	2	5	5
MEP 02A	6,513,819€	5,505,026€	6	6	6
MEP 03	3,580,143€	2,131,408€	4	1	1
MEP 04	3,925,144€	2,459,423€	5	2	2
MEP 05	4,701,366€	3,235,645€	3	4	4

Table A7. Comparison of all variations in CG 400+B6 (high-time-preference scenario) (2). The colors indicate the lowest (green) and highest values (red), gradation for the ranking in-between.

Variation	eLCC (No D)	eLCC (Incl. D)	fLCC	eLCC No D/fLCC	eLCC Incl. D/LCC
MEP 01	1,088,355€	710,178€	694,507€	157%	102%
MEP 02	1,682,423€	1,321,373€	735,427€	229%	180%
MEP 02A	1,774,694€	1,525,775€	798,743€	222%	191%
MEP 03	842,553€	485,090€	744,455€	113%	65%
MEP 04	929,199€	567,529€	796,000€	117%	71%
MEP 05	1,259,322€	897,652€	748,330€	168%	120%
Variation	**fLCC + eLCC (No D)**	**fLCC + eLCC (Incl. D)**	**Ranking Based on fLCC**	**Ranking Based on fLCC + eLCC No D**	**Ranking Based on fLCC + eLCC Incl D**
MEP 01	1,782,862€	1,404,685€	1	3	3
MEP 02	2,417,850€	2,056,800€	2	5	5
MEP 02A	2,573,437€	2,324,518€	6	6	6
MEP 03	1,587,008€	1,229,545€	3	1	1
MEP 04	1,725,199€	1,363,529€	5	2	2
MEP 05	2,007,652€	1,645,982€	4	4	4

Table A8. Comparison of all variations in CG 400+B6 (low-time-preference scenario) (2). The colors indicate the lowest (green) and highest values (red), gradation for the ranking in-between.

Variation	eLCC (No D)	eLCC (Incl. D)	fLCC	eLCC No D/fLCC	eLCC Incl. D/LCC
MEP 01	10,031,652€	3,109,839€	2,275,466€	441%	137%
MEP 02	16,407,963€	9,798,936€	2,795,097€	587%	351%
MEP 02A	17,328,600€	12,767,399€	3,623,491€	478%	352%
MEP 03	7,662,784€	1,118,765€	2,912,465€	263%	38%
MEP 04	8,539,929€	1,919,577€	3,130,728€	273%	61%
MEP 05	11,558,841€	4,938,490€	2,741,389€	422%	180%
Variation	**fLCC + eLCC (No D)**	**fLCC + eLCC (Incl. D)**	**Ranking Based on fLCC**	**Ranking Based on fLCC + eLCC No D**	**Ranking Based on fLCC + eLCC Incl D**
MEP 01	12,307,118€	5,385,305€	1	3	3
MEP 02	19,203,060€	12,594,033€	2	5	5
MEP 02A	20,952,091€	16,390,891€	6	6	6
MEP 03	10,575,249€	4,031,229€	3	1	1
MEP 04	11,670,656€	5,050,305€	5	2	2
MEP 05	14,300,230€	7,679,879€	4	4	4

Appendix C. Weighting of Oekobaudat 2020-II Data by Monetary Valuation

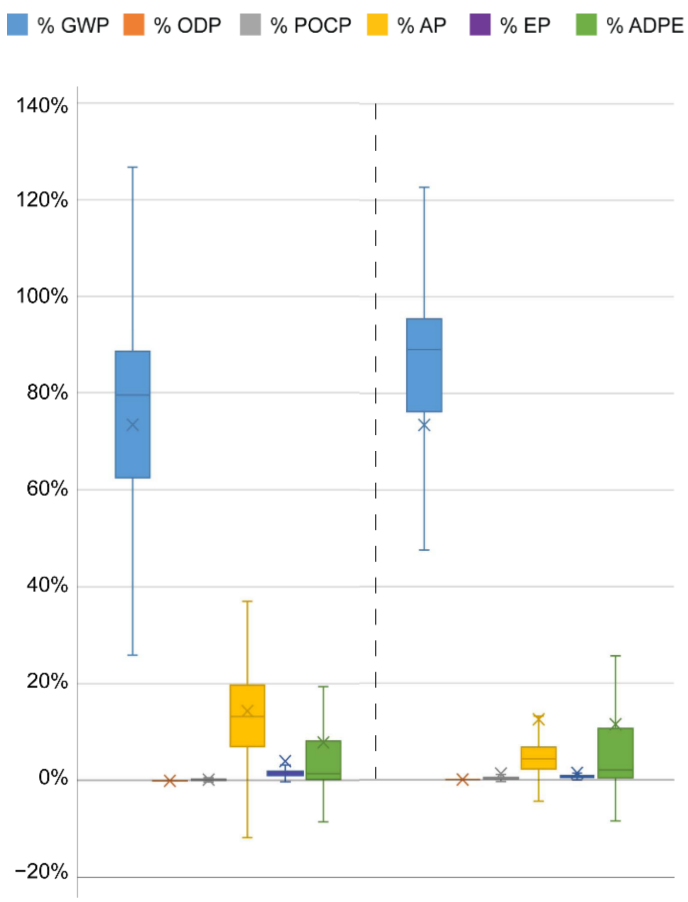


Figure A1. Weighting of ecological indicators resulting from **minimum** (left) and **maximum** (right) monetary valuation for **CG 300** and life cycle phases A1–A3, based on Oekobaudat 2020-II [26].

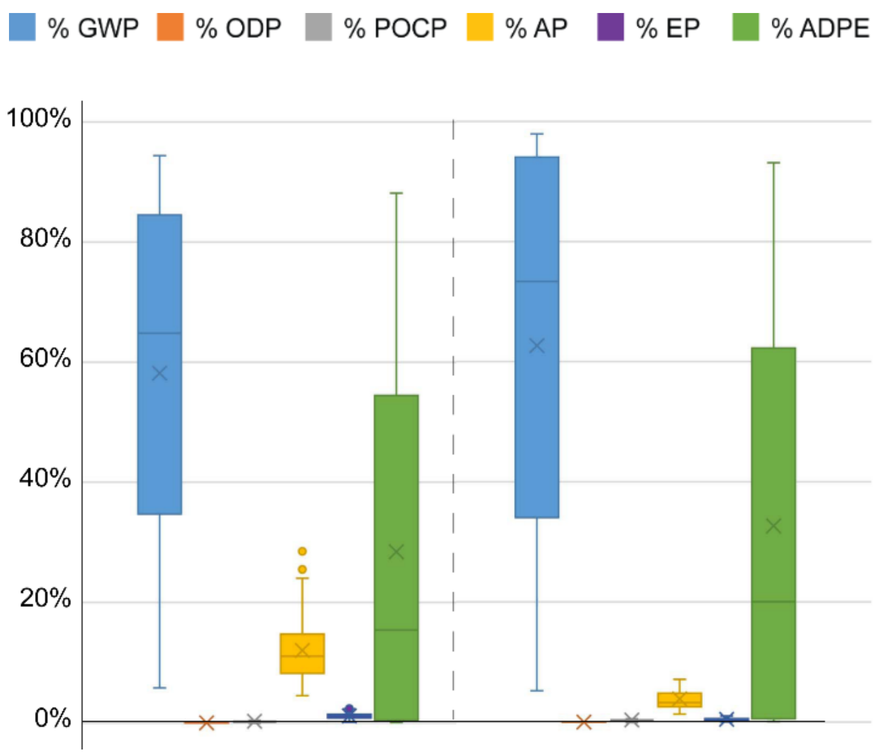


Figure A2. Weighting of ecological indicators resulting from **minimum** (left) and **maximum** (right) monetary valuation for **CG 400** and life cycle phases A1–A3, based on Oekobaudat 2020-II [26].

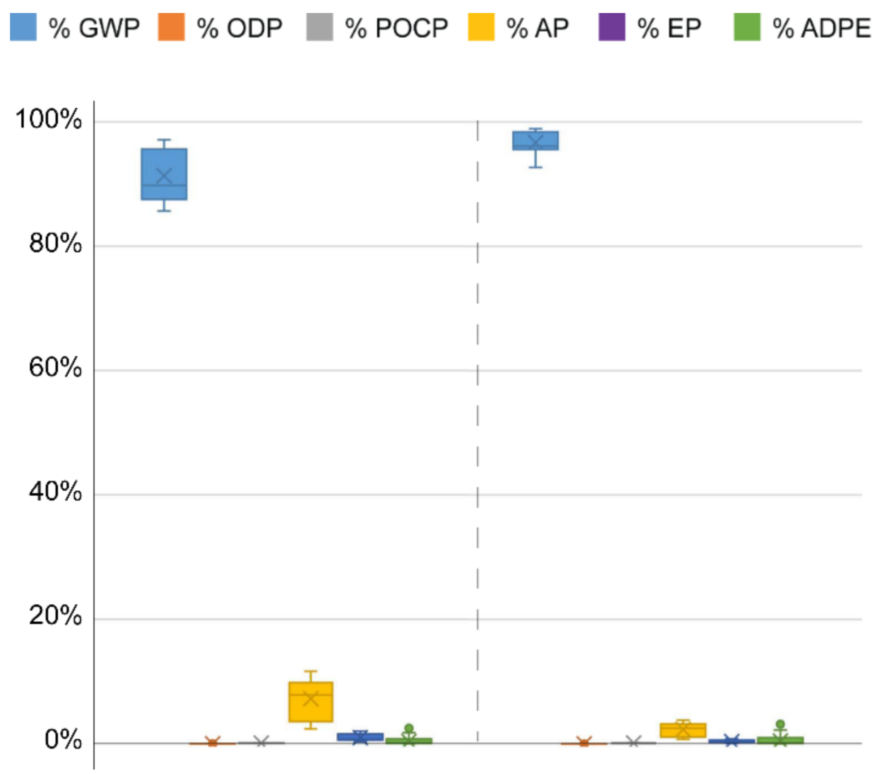


Figure A3. Weighting of ecological indicators resulting from **minimum** (left) and **maximum** (right) monetary valuation for life cycle phase B6 (**non-renewable sources**), based on Oekobaudat 2020-II [26].

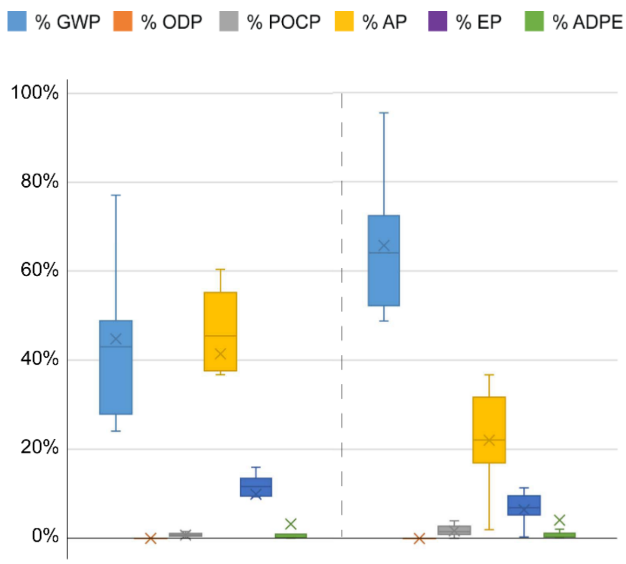


Figure A4. Weighting of ecological indicators resulting from **minimum** (left) and **maximum** (right) monetary valuation for life cycle phase B6 (**renewable sources**), based on Oekobaudat 2020-II [26].

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Uncertainty Analysis of Embedded Energy and Greenhouse Gas Emissions Using BIM in Early Design Stages

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Received: 25 February 2020; Accepted: 20 March 2020; Published: 26 March 2020

Abstract: With current efforts to increase energy efficiency and reduce greenhouse gas (GHG) emissions of buildings in the operational phase, the share of embedded energy (EE) and embedded GHG emissions is increasing. In early design stages, chances to influence these factors in a positive way are greatest, but very little and vague information about the future building is available. Therefore, this study introduces a building information modeling (BIM)-based method to analyze the contribution of the main functional parts of buildings to find embedded energy demand and GHG emission reduction potentials. At the same time, a sensitivity analysis shows the variance in results due to the uncertainties inherent in early design to avoid misleadingly precise results. The sensitivity analysis provides guidance to the design team as to where to strategically reduce uncertainties in order to increase precision of the overall results. A case study shows that the variability and sensitivity of the results differ between environmental indicators and construction types (wood or concrete). The case study contribution analysis reveals that the building's structure is the main contributor of roughly half of total GHG emissions if the main structural material is reinforced concrete. Exchanging reinforced concrete for a wood structure reduces total GHG emissions by 25%, with GHG emissions of the structure contributing 33% and windows 30%. Variability can be reduced systematically by first reducing vagueness in geometrical and technical specifications and subsequently in the amount of interior walls. The study shows how a simplified and fast BIM-based calculation provides valuable guidance in early design stages.

Keywords: early building design; life cycle assessment (LCA); building information modeling (BIM); embedded greenhouse gas emissions; embedded global warming potential; life cycle energy analysis; life cycle energy assessment; design assessment; embedded primary energy

1. Introduction

Buildings play an important role in providing comfortable conditions for human life and work. Therefore, it is not surprising that constructing and operating them and the related infrastructure consumes a large part of global resources [1], both in terms of material as well as energy [2], and directly and indirectly emits 40% of global greenhouse (GHG) gas emissions [3]. Hence, the building industry is one of the focus areas for the reduction of energy demand and GHG emissions [4]. Life cycle energy demand by and emissions from buildings consist of two components—embedded (also known as embodied) and operational [5]. Due to the long lifespan of buildings, conditioning the building is responsible for the largest share of energy consumption and emissions of existing buildings. Therefore, efficiency efforts have focused on the operation phase [4]. However, with increasing energy efficiency and a growing share of renewable energy for building operation, embedded energy and environmental impacts gain importance. The European directive on the energy performance of buildings [6] requires all newly constructed buildings in Europe to be nearly zero energy buildings (NZEB) starting in the year 2020. This means that new buildings will consume almost no non-renewable energy during their operation. Consequently, all non-renewable energy demand and thus the largest share of GHG emissions will occur during the construction, maintenance, and end-of-life phases. Recent studies underline this trend [5,7].

To evaluate the environmental performance of building throughout their entire life cycle, life cycle assessment (LCA) is in the process of being established in the building industry [8]. However, unlike operational energy calculations, LCA is not part of standard planning processes. Even operational energy calculations are conducted as late as possible in the design process when more information about the future building is available, mainly to show compliance with standards [9]. LCA calculations are not mandatory except for certification purposes by a green or sustainable building certification system, such as DGNB (Deutsche Gesellschaft für nachhaltiges Bauen, German Sustainable Building Council) [10] or LEED (Leadership in Leadership in Environmental and Energy Design) [11]. In light of the increasing importance of the construction, maintenance, and end-of-life phases, both standardization and tools for evaluation are needed [12].

Energy and environmental performance evaluation throughout the building design process bears significant improvement opportunities [13], but at the same time, it poses multiple challenges. The assumptions made throughout the initial design stages and the decisions based on these assumptions have significant influence on building performance [14,15]. As the potential to minimize energy demand and GHG emissions is greatest in these early design stages [16,17], there is increasing demand for performance evaluation in these stages. However, there is a lack of information about future building, and information, which can serve as a basis for analysis, is uncertain. To deal with this vagueness, sensitivity analyses should be employed in order to visualize uncertainties in the results as well as influential parameters contributing significantly to result uncertainties [18]. Moreover, for the designer, it is also valuable to see which building parts contribute most to the overall quantity of energy demand and environmental impact. For the purposes of this study, we use the term contribution analysis for this calculation.

Uncertainty analysis has recently been used extensively in building (operational) energy assessment [19]. For LCA, which includes embedded energy and environmental impact calculations, uncertainty analysis is less common [20], but with increasing relevance of embedded life cycle phases of buildings, it is becoming an important research field. Sources of uncertainty in embedded energy and impacts overlap with uncertainties for operational energy mainly when they pertain to exterior building parts [21]. Of the different uncertainties present in LCA studies—parameter uncertainty, model uncertainty, and scenario uncertainty [22]—this study is concerned with uncertainty in the building design parameters.

Uncertainty analysis consist of a sampling step (preprocessing), calculation (uncertainty propagation), and final analysis (post-processing) of the results [23]. The sampling step involves varying the input parameters according to their distribution functions. Monte Carlo simulation is one of the most commonly used sampling technique in probabilistic calculations, generating random samples based on the input parameters' distribution functions [24]. Subsequently, the uncertainties are propagated, i.e., the output results for each sample and mean value and variance of all output values are calculated. Global sensitivity analysis then identifies how much input parameter uncertainties contribute to output variance. Only if sampling is based on distribution functions, global sensitivity analysis is possible [25]. Global sensitivity analysis techniques usable in LCA include (squared) standardized regression coefficients, squared Spearman correlation coefficients, or Sobol indices [25].

Full building LCA calculations require detailed information about the materials used in the building, construction processes, energy demand and generation, and end-of-life scenarios. Although there are building characteristics that influence both embedded and operational energy and impacts, the calculation methods for each are essentially different: operational energy demand ideally requires dynamic thermal simulation taking into account the exterior conditions (climate, shading provided by surrounding buildings, etc.). The calculation of environmental impacts for building operation uses the operational energy demand as an input value and calculates the related environmental impact by taking the energy sources (mechanical systems and energy carrier) into account. Embedded energy and environmental impact calculations, in contrast, are essentially matrix calculations whose complexity stems from the amount of data and information required. To reduce this complexity to a manageable level, aggregated data is provided in building LCI/LCIA databases such as the Oekobaudat [26]. This paper explores in detail the analysis of embedded energy and GHG emissions in early design stages in addition to the uncertainty analysis of relevant parameters for both operational and embedded energy published in Harter et al. [21]. The related operational energy calculation is described in detail by Singh and Geyer [27].

Existing LCA and energy calculation tools work well for later design stages when the building's shape and materials are established in detail [28]. Current methods to calculate embedded energy and impacts do not lend themselves to early design stages, as they require more information input than commonly available at an early stage. In early stages, missing information in terms of both materials and missing building elements have to be estimated. However, estimations require expert knowledge and lack transparency for the designer. Moreover, design uncertainties are not systematically taken into account [20]. In this context, building information modeling (BIM), a well-established modeling technology with 3D-data including geometry and information on different levels [29], offers several opportunities: it facilitates managing the amount of data needed for calculations and providing automated or semi-automated calculations [30,31].

In early stage performance analysis, few, if any, variants of a project are evaluated, as standard calculations are lengthy and hence time-intensive. Commonly, only a handful of previous sample projects are available, providing guidance from experience to find the most relevant parameters. However, as various buildings are only comparable to a limited extent, even normalization to usable floor area and one building type does not provide satisfying standard values [32], as influential parameters can differ from project to project. Hence, the aim of this project is the development of a tool for engineers and designers to provide a project-specific quick estimate of the embedded energy and GHG emissions of the building using a limited number of background datasets, but taking uncertainties caused by design vagueness into account. Subsequently, this will be integrated into the overall performance evaluation such that trade-offs between operational and embedded life cycle phases can be visualized and other criteria (cost, fire safety, etc.) are taken into account.

This paper presents the calculation methods and our sample project in Section 2, starting with the LCA method (Section 2.1), subsequently describing the integration into BIM (Section 2.2) the sensitivity and contribution analysis (Section 2.3), and finally the sample project (Section 2.4). We split the results, Section 3, into three parts. In Section 3.1, we tackle the question of which parameter uncertainties contribute the most to result uncertainties (sensitivity analysis). Section 3.2 analyses the contribution of the building parts, i.e., which parts contribute the most to total embedded energy and environmental impacts (contribution analysis). Section 3.3 tests the influence of a different material choice for the building part with the most contribution to GHG emissions. Section 3.4 evaluates the order of magnitude of average total rough estimate results and validates them against a complete LCA and a simplified manual LCA of the final building design. Section 4 discusses the results, describes the limitation of this project, and provides an outlook toward future research.

2. Methods

2.1. Life Cycle Assessment (LCA)

Building LCA in Europe is standardized per the norms DIN EN ISO 14040 (Environmental management—Life cycle assessment—Principles and framework) [32] and DIN EN 15978 (Sustainability of construction works—Assessment of environmental performance of buildings—Calculation method) [33]. The norm DIN EN ISO 14040 provides the general framework, structuring LCA into four steps: goal and scope definition, life cycle inventory, life cycle impact assessment, and reporting. Our calculations follow this standard, with the goal defined as the comparison between design variants and scope as life cycle primary energy (PE) analysis and analysis of GHG emissions. The life cycle inventory was conducted with a quantity takeoff from an IFC model and a link to Oekobaudat [26]. For the purposes of this study, we translated required Oekobaudat datasets into an SQL database, which provide PE and global warming potential (GWP) values. We included the following building phases: A1–A3 production (including raw materials supply, transportation, manufacturing), B4 replacement, and C3–C4 end-of-life (waste processing and disposal), as defined by DIN EN 15978 [33]. Phase D, reflecting end-of life credits and loads from reuse, recovery, recycling, was calculated separately and is not included in total results. Values for A1–A3, C3–C4, and D come directly from Oekobaudat, whereas phase B4 is related to the reference service life of the building components. For Oekobaudat data, it is mandatory that for construction materials life cycle stages A1–A3 are included. Whenever neither data for life cycle phases C3 nor C4 was included in specific datasets, we used generic end-of-life processes such as construction waste processing. An example for this is mineral wool, for which the generic dataset "construction rubble landfill" provides end-of-life impacts.

We considered building parts (Table 1) that typically contain the largest share of building materials [32]. Reference service life (RSL) lengths of materials were combined for building parts following the definitions used in German LCA studies conducted for building certification [34] which is based on [35]. For the internal walls, instead of the 50-year RSL of gypsum boards, we assumed a conservative value (20 years) for office buildings, for which the interior is renewed more often than every 50 years due to a change in user or for reasons of representativeness. The study period is 50 years, as this is the standard defined by DGNB [36] and BNB (Bewertungssystem Nachhaltiges Bauen, Sustainable Building Certification System) [37] certification systems and used by the majority of recent building LCA studies [38].

Table 1. Building parts included and reference service life (RSL) considered.

Building part	Structure	Insulation	Windows	Internal
Elements included	Ground slab Floor slabs Exterior walls Roof slab	Exterior insulation: Ground slab Exterior walls Roof	Frames (Triple) glazing	Interior walls
RSL (years)	>50	40	40	20

We considered result values for PE demand in megajoules (MJ), split into renewable (PERT) and non-renewable (PENRT) primary energy, and global warming potential (GWP) in kg CO_2-eq. This choice is based on the fact that buildings contribute significantly to global energy demand and GHG emissions (Section 1). PENRE, the energy resources part of PENRT, and GWP are related because the burning of fossil fuels emits carbon dioxide and thereby contributes to global warming. Therefore, we additionally looked for a possible correlation between PENRT and GWP.

2.2. Integration into BIM

The LCA calculations described in Section 2.1 rely on BIM methods developed within the research group EarlyBIM [39]. The calculation process involves quantity takeoffs of the main building parts from an early design stage IFC model, including exterior wall areas, base plate area, roof area and floor slab areas (Figure 1). The sampling process uses these quantity takeoffs in conjunction with vagueness defined by the designer. To provide information about geometric and semantic uncertainties in BIM-models, the meta-model allows specification of vagueness of the overall building model and building components [40]. We use this meta-model to integrate vagueness into PE and GWP calculations. The designer and the consulting engineer provide additional information needed for the calculations, such as window-to-wall-ratio or u-values (Table 2). This information also contains vagueness according to the design stage.

As described, parameters termed "geometry" are derived from the BIM model. The parameter "interior walls" represents the (volume) percentage of interior walls of total interior volume of the building (i.e., gross volume minus volume of exterior walls, base plate, floor slabs, and roof). The window-to-wall-ratio is the ratio of transparent area to total exterior wall area. The technical specifications depend on consultant input. U-values of exterior building parts determine the energy standard of the building. "Construction thicknesses" represent the thickness of the structural elements (i.e., excluding insulation), depend on the structural requirements of the building parts, and are subdivided by building part (base plate, floor slabs, exterior walls, and roof). Finally, the reinforcement amount is needed for concrete building parts only and is defined to be the mass (kg) of reinforcing steel per volume (m^3) of concrete. As we are analyzing embedded impacts in more detail, the number of parameters is reduced compared to our previous study concerned with LCEA [21]. Also, the reduced number of parameters allows us to regroup them differently providing a more specific analysis.

The method is integrated with the concept of building development levels (BDL) developed within the EarlyBIM research group [41,42]. BDL describes the project-specific maturity of a BIM model. This concept was developed, because the commonly used term level of development (LOD) specifies the geometric and semantic information content of building elements but explicitly not the entire building model [43]. On the contrary, models typically are multi-LOD-models, i.e., they consist of elements of various LODs throughout the design process. The BDL concept was developed to enable the project team to specify required information and vagueness on a building level during the design process. The LOD concept is used as a basis for the elements contained in the models. Starting with BDL1, when no 3D information is available yet, models are increasingly enriched with geometric and semantic information with decreasing vagueness of the contained information. As the BDL specification does not contain values for LCA calculations, we defined a set of input parameters needed for our calculations (Table 2) and grouped them according to the design process, as a group of parameters tends to be defined at the same time by the same actor. For each parameter, a mean value and vagueness (percentage of possible deviation) are provided. Quantities and specifications in conjunction with corresponding vagueness serve as input parameters for the following sensitivity and contribution analysis.

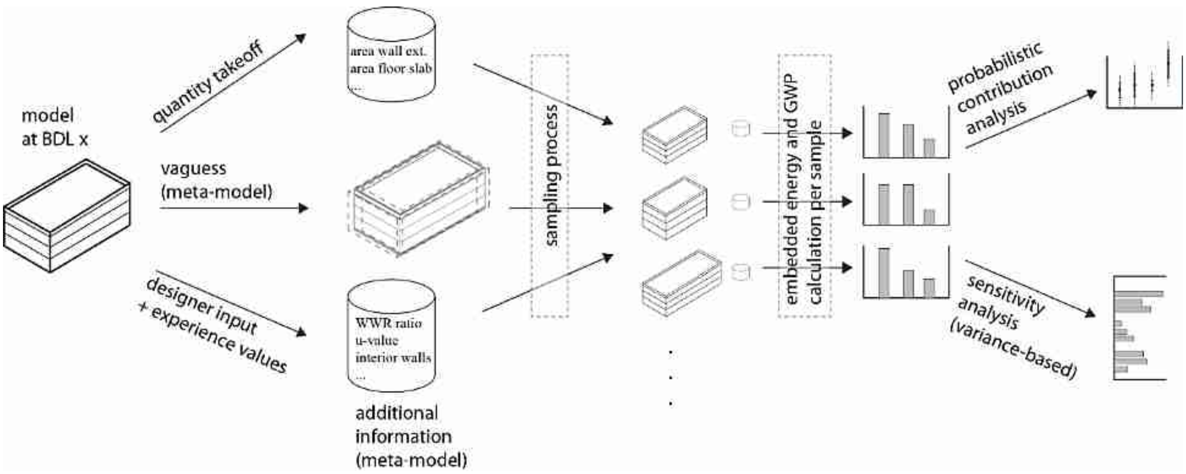

Figure 1. Workflow for embedded energy and input calculation with uncertainty.

2.3. Sampling Process, Sensitivity, and Contribution Analysis

The input parameters (Table 2) for the LCA calculation elements are subsequently sampled using a uniform distribution of the design parameters as recommended by Kristensen and Petersen [44] for design uncertainties. All parameters are varied simultaneously (Monte Carlo), such that each building sample consists of a unique combination of parameter values. The sampling sets are generated within MatLab using the ERAdist MCS (normal MOM) probability distribution class developed by Geyer et al. [45]. Given the very short calculation time (less than 30 seconds for the initial calculation of one BDL, less than five seconds for subsequent calculation and generation of graphs), we chose a generous number of sampling sets (10^5). For each sample, the LCI/LCA results are calculated for primary energy (PENRT, PERT) and GHG emissions (GWP).

Table 2. Input parameter groups.

Geometry (Areas) [1]	Interior [2]	Windows [2]	Technical Specifications [3]
Ground slab	Interior walls (%)	WW-ratio	u-values
Floor slabs	-	-	Construction thicknesses
Exterior walls	-	-	Reinforcement amount
Roof	-	-	-

[1] Extracted from building information modeling (BIM) model (IFC); [2] Additional designer input (experience values); [3] Additional consultant input (experience values).

For the subsequent variance-based sensitivity analysis, we calculated first-order sensitivity indices, showing how input parameter uncertainties influence result uncertainty. The sum of the sensitivity coefficients should be equal or close to 100%, as it is assumed that higher-order effects are close to zero. This sensitivity analysis provides guidance to the designer which uncertainties to systematically reduce in order to improve exactness of calculations.

Additionally, we conducted a contribution analysis. We calculated the means and standard deviation per building part (Table 1) and for the whole building to see which building parts contribute the largest share to energy demand and GHG emissions. This contribution analysis shows the relevance of each building part for the total outcome and guides the designer toward the building parts with the highest overall reduction potential. Contribution and sensitivity analysis are related—parameters influencing the most relevant building parts will also prove to exhibit comparatively larger sensitivities.

According to Raskin and Tylor [46] various terms for uncertainty are used in both colloquial and scientific language, with their definitions themselves uncertain. We use the term uncertainty—as suggested in Hawer at al. [47]—as an umbrella term for all types of uncertainty such as fuzziness, vagueness, ambiguity, etc. To further specify design uncertainty separated from other uncertainties inherent in the BIM model we used the term vagueness. In this, we differ from Abualdenien and Borrmann [41] where design uncertainty was referred to as fuzziness. Both concepts are, however, closely connected according to [48]. In our study, vagueness is due to decisions not yet made in the design process. It is assumed that this vagueness is eliminated by the time the building has been built. Of course, even the as-built state of a building contains uncertainties due to e.g., construction tolerances or the dynamic nature of u-values.

Huijbregts et al. [22] identified three types of uncertainty in LCA studies—parameter, scenario, and model uncertainty. Of these, our study is concerned with parameter uncertainty, termed vagueness, as explained above. Uncertainties in the underlying scenarios or assumptions, such as length of the study period or reference service lives, were not included in our sensitivity analysis, as these are outside of the influence of the architect or engineer during the planning process. Rasmussen et al. [49] provide an overview of the influence of these choices. Neither are LCA models, such as characterization methods, varied in our study, as the employed database, Oekobaudat [26], does not provide data for this, and designers cannot influence these choices. Therefore, the underlying datasets are fixed in this study, in contrast to Tecchio et al. [50,51], which employed the method of structured under-specification to capture uncertainty in material choice in early design stages.

The value corridors for the input parameters determine the characteristics of the building to be analyzed, covering a wide range of building forms and construction types. For example, the window-to-wall ratio represents the type of façade, such as fully glazed curtain wall or opaque façade with few window openings.

2.4. Case Study

We applied our method to the office building "FTmehrHAUS" by Ferd. Tausendpfund GmbH, using BIM models at BDL 2, 3, and 4. The case study is a three-story, rectangular-shaped building with a gross floor area of approximately 1200 m² located in Regensburg, Germany. The building was built in 2016 using three different wall types for each story of exterior wall: concrete, masonry and sand lime stone, each with an exterior insulation and finishing system (EIFS). The building's structure is made of reinforced concrete. Table 3 shows the input values for the calculations representing the sample building. The building's energy standard exceeds the requirements of the current German energy saving ordinance [52].

Table 3. Input values representative of the sample building.

Parameter group	Parameter	Mean Value	Vagueness at BDL2
Geometry	Ground slab area	405 m²	±10%
	Floor slab area	810 m²	±10%
	Exterior wall area (total)	840 m²	±10%
	Roof area	405 m²	±10%
Interior	Interior Walls	6%	±25%
Windows	WW-ratio	30%	±25%
Technical Specifications	u-value (ground slab)	0.19 W/m² × K	±25%
	u-value (ext. wall)	0.18 W/m² × K	±25%
	u-value (roof)	0.15 W/m² × K	±25%
	Construction thickness (ground slab)	0.35 m	±25%
	Construction thickness (ext. wall)	0.20 m	±25%
	Construction thickness (floor slabs)	0.25 m	±25%
	Construction thickness (roof slab)	0.25 m	±25%
	reinforcement	140 kg/m³	±25%

Initial vagueness percentages were chosen to represent a rough design of the case study building at BDL2. Geometric uncertainties were chosen to be lowest, as we assumed that the rough volume is decided upon early in the process. However, these are project-specific and can vary greatly from project to project, as they depend on the specific site conditions. For example, it is possible that the building footprint is fixed by a development plan, such that the vagueness of the ground and floor slab areas would be zero. All other vagueness percentages were set to 25% to represent a reasonable range of values in order to test the method. These, too, can differ from project to project, as there might be specific requirements, such as an ambitious energy standard with very low u-values. Vagueness is subsequently reduced following guidance from the sensitivity analysis. The results of this case study cannot be generalized for the above reasons, but the method can be applied to other buildings.

For validation purposes, a standard LCA calculation of the project based on the execution drawings and additional information from the client was conducted. To maintain comparability with the probabilistic calculation, as described in Section 2.1, we considered one uniform wall type (concrete with EIFS) for the entire exterior wall. The Oekobaudat version (2016-I), study period, and products' reference service lives are identical with the respective framework for the probabilistic calculation. For comparison with the sampling and uncertainty propagation results, all data was input into the tool eLCA [53], from which results were exported in csv format and split into the four building parts structure, insulation, windows, and internal (Table 1).

3. Results

3.1. Sensitivity Analysis

Figure 2 shows uncertainties and resulting uncertainty contribution for each parameter group according to BDL 2, 3, and 4. Exact numbers are listed in Appendix A, Table A1. Input parameter uncertainties are strategically reduced with increasing BDL to reduce overall uncertainty in the results. Note that the sum of uncertainty contribution is always close to one (100%) (see Section 2.3). It has to be kept in mind that Figure 2 shows uncertainty contribution, not overall result uncertainty. The latter is shown in Section 3.2.

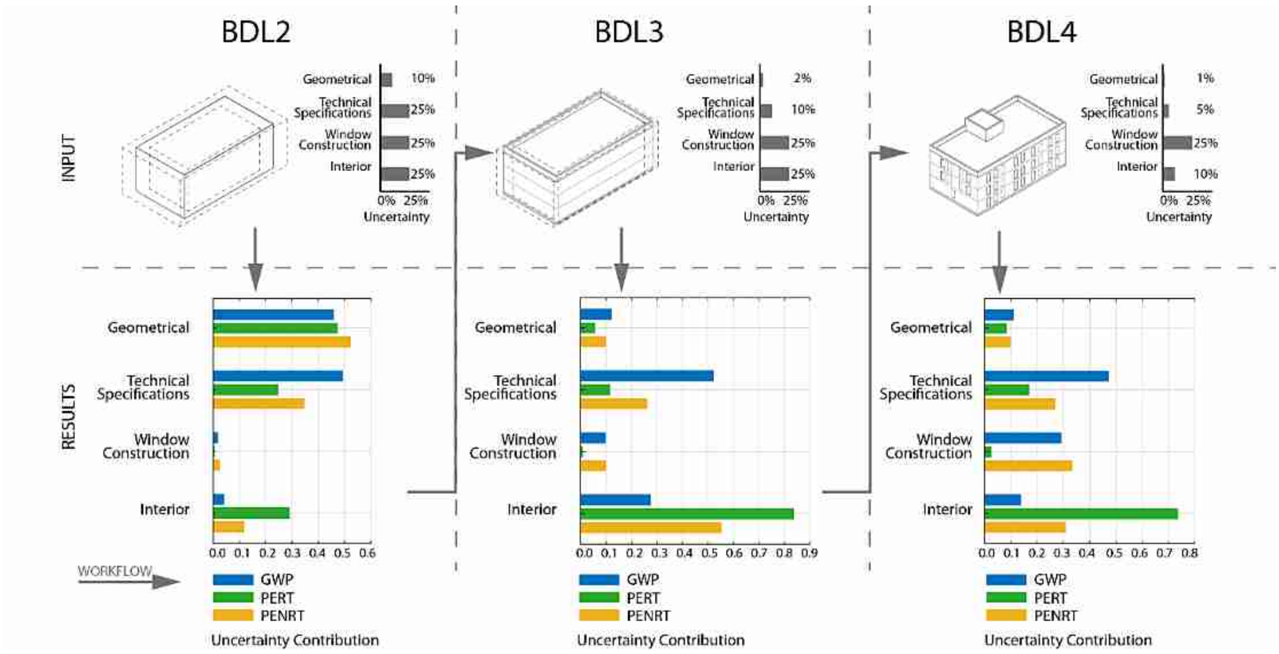

Figure 2. Input uncertainty (vagueness) in parameter groups and resulting uncertainty contribution for a rectangular building shape and reinforced concrete structure; exact numbers are listed in Appendix A, Table A1.

In BDL 2, result uncertainties are highly dependent on the geometrical parameter uncertainties, followed by the uncertainties in technical specifications. Hence, these input uncertainties are reduced for BDL3 in order to increase the accuracy of the results. In BDL3, result uncertainties, now overall lower than in BDL2, are strongly dependent on interior (for PERT and PENRT) and still on technical specifications (for GWP). Therefore, uncertainty in these parameters is reduced for BDL4. In BDL4, the uncertainty contribution of windows increases for GWP and PENRT, as all other uncertainties are small. In this process, it is clear that there are trade-offs involved when decreasing uncertainties simultaneously: reducing uncertainties in one parameter increases the contribution of another parameter, e.g., uncertainty contribution of the technical specifications to GWP does not change, as the uncertainty contribution of interior decreases simultaneously. However, overall uncertainty decreases significantly with increasing BDL (see Section 3.2).

Overall, an ideal picture would show equal sensitivities for all parameters. This, however, is impossible due to the differing nature of the indicators considered. Between PENRT and GWP, parallels can be identified. This is not surprising, as the use of fossil energy sources (represented by the indicator PENRT) contributes largely to GHG emissions, represented by the indicator GWP. However, GWP and PENRT do not correlate entirely, as there are other sources of GHG emissions, such as the chemical process of clinker production, which is a step in the process of cement production. PERT behaves differently from both PENRT and GWP: Results' uncertainty for PERT is to the largest extent due to the uncertainty of the amount of interior walls, starting from BDL3. In turn, the uncertainty in window construction is insignificant for PERT uncertainty. This is related to the fact that the materials used in interior wall construction (gyp board) have a comparatively high content of PERT, whereas the materials used in window construction (PVC, glass) do not.

The sensitivity analysis guides the workflow of strategic uncertainty reduction and thereby reduces overall uncertainties. From the BDL 2 analysis, the planning team receives the information that geometric uncertainties and technical specifications are the main sources for result uncertainty. Therefore, planning efforts should focus on these aspects to arrive at BDL3. Subsequently, the layout of the interior walls needs to be specified in addition to the aforementioned parameters. These steps increase reliability of results as will be shown in the following Section 3.2.

3.2. Contribution Analysis

This section analyses the contribution of functional parts of the building to show how the sensitivity analysis indicates where in the building the highest potential to reduce PE demand and GHG emissions is located. This pertains to the indicator GWP for GHG emissions and PERT and PENRT for primary energy use. Building parts are defined in Table 1.

Figure 3 shows the results for the sample building for BDL2 and BDL4. BDL 3 was omitted as results lie between BDL2 and BDL4 and do not contain additional information regarding the building part contribution.

First, the overall reduction of result uncertainty is clearly visible. Average values stay constant as we did not change any of the mean input values. The contribution of the building parts changes insignificantly from one BDL to the next. This, too, is an expected result for the same reason as the (mean) input values stay the same.

Second, the contribution analysis can guide architects and consultants towards strategic building parts, i.e., the parts that should be considered primarily when looking for ways to reduce energy demand and GHG emissions. To render a building part truly strategic a second condition must be fulfilled: alternative materials with lower PE content and GHG emissions need to be available. For example, for a concrete base plate, no alternative materials are available. However, alternatives in structural design either providing a different kind of foundation or an alternative concrete/reinforcement combination might be available. Hence, this study provides guidance toward the building parts with the highest influence but does not provide design assistance, i.e., it entrusts the design team with determining if alternative solutions are available. For GWP and PENRT, the building's structure, made of reinforced concrete, clearly emerges as a decisive part, contributing half of the building's GWP and 37% of PENRT. Second, windows are relevant and thirdly, interior walls. Insulation plays a lesser role despite the above average energy standard of the building.

As a building part's contribution depends on the materials used for each building part, reducing overall emissions without changing any of the input parameters requires looking at alternative building materials.

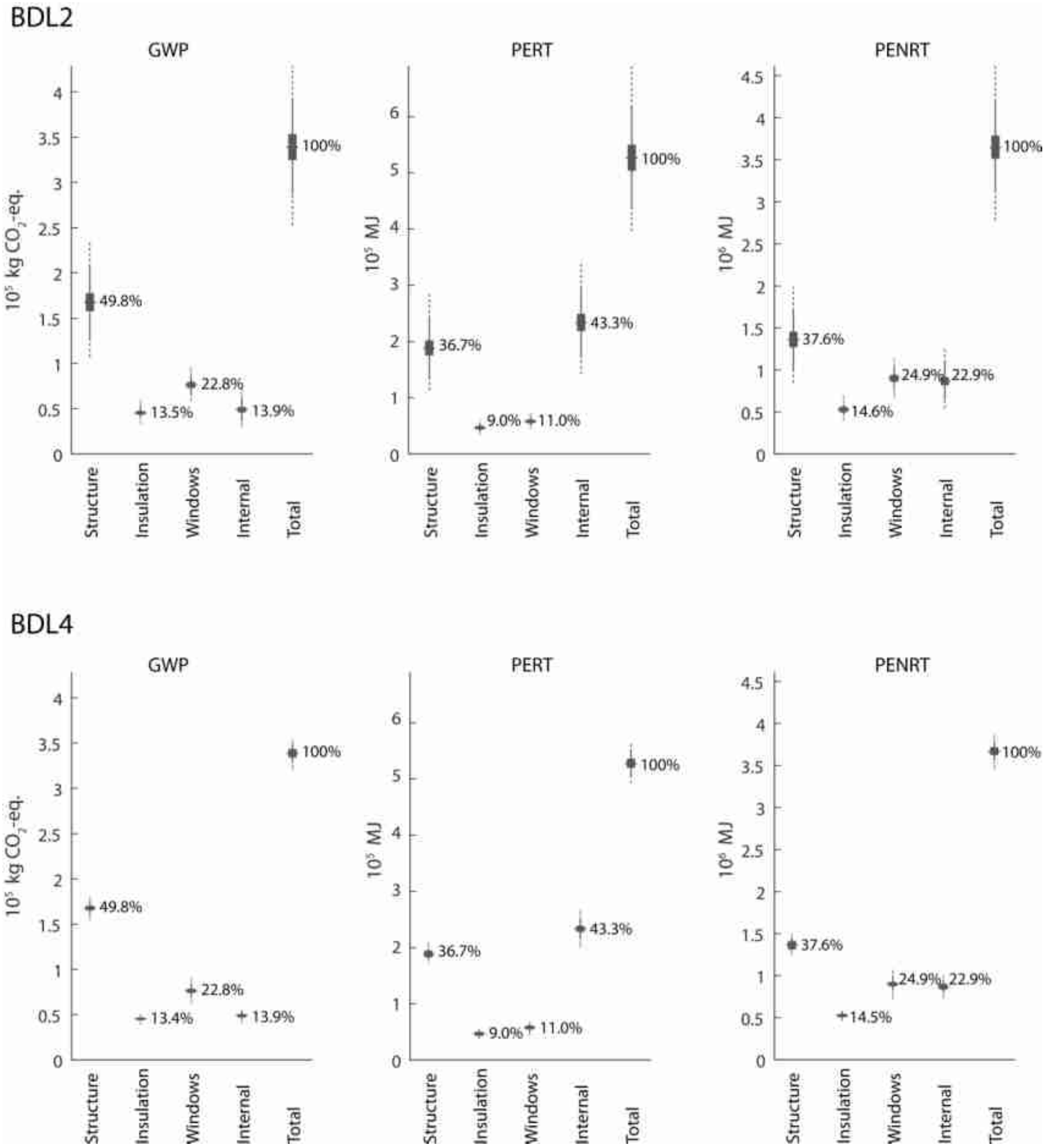

Figure 3. Box plots of sample building contributions and uncertainties for a reinforced concrete building: global warming potential (GWP), renewable primary energy (PERT), and non-renewable primary energy (PENRT). The mean is represented by a horizontal line, the interquartile range by a thick line, min and max are connected by a thin line and outliers are shown as dotted lines.

3.3. GWP Reduction Potential

Since the structure is the largest contributor to total GWP and the use of wood is known to reduce GHG emissions, we ran the sensitivity and contribution analyses with wood instead of reinforced concrete. In general, this alternative is only available when fire safety requirements allow the use of wood (which is the case for our case study as we deal with a building of a low fire safety class) and takes into account that some parts cannot be replaced such as the base plate. All results are listed in Appendix A, Table A2. This case study shows the effect of a different material choice. Overall, changing the structural material reduces GWP by 25% and PENRT by 10% while at the same time increasing PERT by 123% (see Figure 4). This result is in line with previous LCA studies, which unequivocally state that the use of wood structures reduces GHG emissions [54]. The large increase in PERT is due to the calculation background used in Oekobaudat: the sunlight absorbed by the trees is attributed to the wood as consumption of renewable energy.

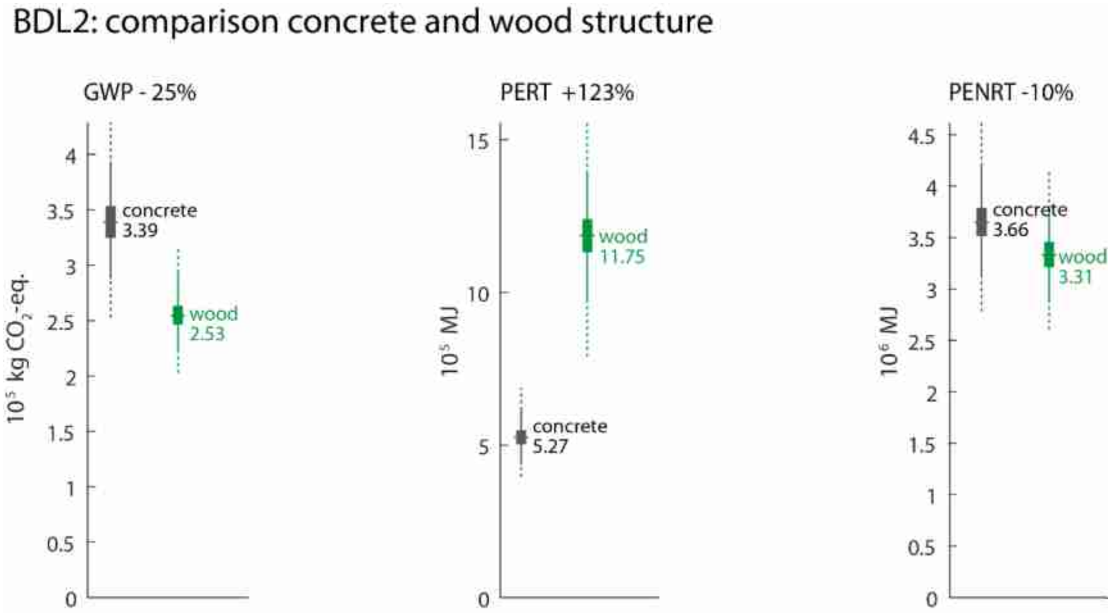

Figure 4. Boxplots of comparison of total values for wood and concrete construction for global warming potential (GWP), renewable primary energy (PERT), and non-renewable primary energy (PENRT). The mean is represented by a horizontal line, the interquartile range by a thick line, min and max are connected by a thin line and outliers are shown as dotted lines.

The analysis also shows that, at BDL2, uncertainties are such that there are reinforced concrete building samples with lower GWP than some of the wood building samples. However, this overlap between the probabilistic results is located outside of the interquartile range. This means that the wood structure is highly likely to perform better in this indicator. For PENRT, the wood structure is still likely to perform better, but the overlaps between the two material options are greater than for GWP. For the indicator PERT, on the other hand, there are no overlaps. Therefore, any sample of the wood building will demand more PERT than any sample of the concrete building. However, PERT is still only roughly 26% of overall PE demand, compared to 12.5% for the concrete building. In other words, total PE demand of the wood building is 7% higher than of the concrete building.

The contribution of the building parts shifts accordingly (Figure 5). The wood structure is responsible for 33% of GHG emissions instead of 50% for the case the reinforced concrete structure. The absolute results for other building parts stay the same, but their contribution increases as the total decreases. For PERT, the same applies reversely: the contribution of the structure doubles from 36% to 73%, reducing the relevance of all other building parts.

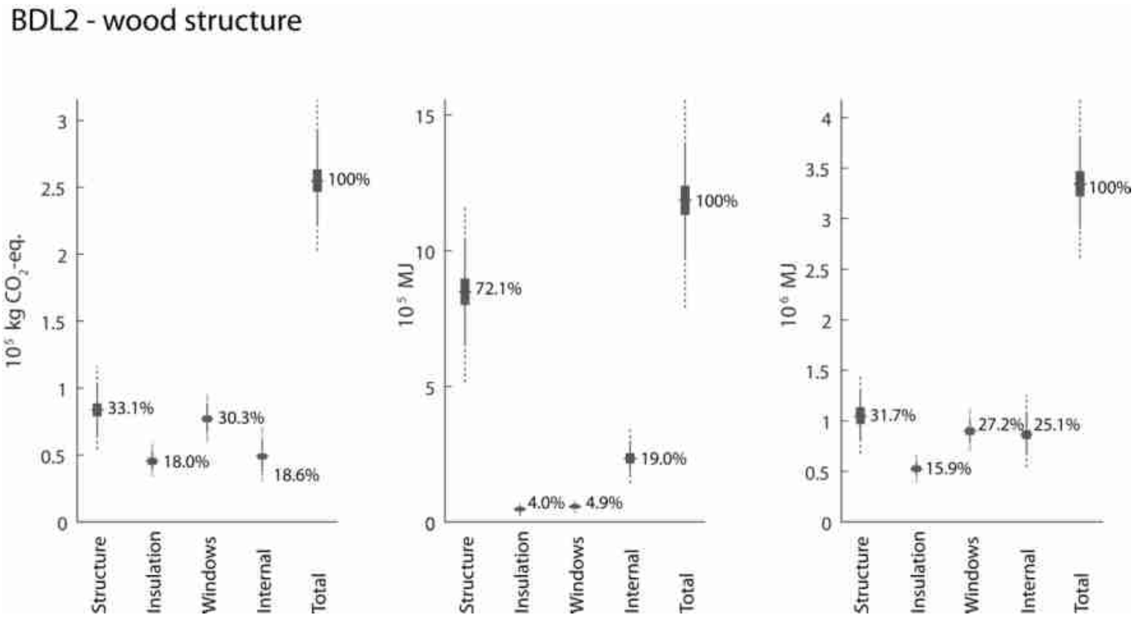

Figure 5. Boxplots of contribution and overall values of wood structure for BDL2 for global warming potential (GWP), renewable primary energy (PERT), and non-renewable primary energy (PENRT). The mean is represented by a horizontal line, the interquartile range by a thick line, min and max are connected by a thin line and outliers are shown as dotted lines.

According to this analysis, the next step to minimize GHG emissions would be to look at other material options for the window frames. This is building-specific and has to be evaluated on a case-by-case basis.

3.4. Order of Magnitude and Validation

Since we are using a simplified model with only few materials, we verified the results with a more detailed LCA calculation based on the execution drawings of the case study. Additionally, we conducted a simplified LCA manually in order to verify the probabilistic calculation. This simplified calculation uses a fixed size of the building matching the mean input values and the same reduced number of materials as the probabilistic calculation. For the probabilistic calculation, mean values of the BDL4 calculation are shown, as these are the least uncertain. However, as described in Section 3.2, mean values are consistent throughout the BDLs.

Table 4 shows the results of the simplified and probabilistic calculations in comparison to the detailed calculation based on the execution drawings. All values are rounded without digits. Hence, the sum of all contribution percentages can differ from 100%, as it does for PERT and PENRT simplified (99%) and PENRT detailed (99%). Simplified and probabilistic calculations generally deliver similar results differing by a maximum of −5% and +8%. This indicates that the probabilistic calculation is by far superior to a manual simplified calculation, as it can calculate 10^5 samples in less than one minute, a task that is virtually impossible for a traditional calculation by hand.

Compared to the detailed calculation, the probabilistic calculation underestimates GWP and PENRT by 27% and 30%, respectively, but does not differ significantly in PERT results. Therefore, we look at GWP and PENRT separately from PERT results. Generally, for GWP and PENRT, detailed results are at the high end of the value corridor of the BDL2 calculation shown in Figure 3. This is to be expected as the probabilistic calculation neglects all finishes and small elements and therefore is restricted to a handful of materials, whereas the detailed calculation is based on 42 different materials. Hence, the absolute values of the calculation should not be used in the planning process, for example to determine compliance to certification benchmarks. Instead, the design process should be based on comparative analyses.

Table 4. Comparison of life cycle assessment (LCA) results of probabilistic, simplified and detailed calculation for the case study.

LCA		GWP [kg CO_2-eq.]		PERT [MJ]		PENRT [MJ]	
Detailed	TOTAL	470,482 (100%)		538,084 (100%)		5,229,523 (100%)	
	structure	45%	212,979	40%	217,507	34%	1,785,981
	insulation	16%	74,065	10%	51,446	21%	1,118,043
	windows	20%	94,727	16%	84,939	21%	1,101,638
	internal	19%	88,710	34%	184,192	23%	1,223,861
Simplified	TOTAL	358,621 (76%)		524,702 (98%)		3,756,157 (73%)	
	structure	49% (+4%)	177,351	37% (−3%)	193,148	36% (+2%)	1,368,205
	insulation	16% (±0%)	50,146	11% (+1%)	60,055	18% (−3%)	674,660
	windows	23% (+3%)	81,115	11% (−5%)	60,239	25% (+4%)	953,488
	internal	12% (−7%)	42,497	40% (+6%)	211,260	20% (−3%)	759,804
Probabilistic (mean, BDL4)	TOTAL	336,788 (73%)		517,086 (96%)		3,619,140 (70%)	
	structure	50% (+5%)	167,852	37% (−3%)	189,709	38% (+4%)	1,361,042
	insulation	13% (−3%)	45,252	9% (−1%)	46,475	14% (−7%)	524,675
	windows	23% (+3%)	76,742	11% (−5%)	56,994	25% (+4%)	902,003
	internal	14% (−5%)	46,943	43% (+9%)	223,908	23% (±0%)	831,419

However, the contribution analysis, i.e., the indication of strategic building parts, differs by +5% (GWP) or –7% (PENRT) or less. The shares of structure and windows are slightly overestimated, the shares of insulation and internal underestimated. At the same time, the ranking of the building parts remains the same as in the detailed model for GWP. For PENRT, it indicates correctly the structure as the main contributor, but differs in the ranking of the other building parts, as their contributions are very close (21%, 21%, and 23%) in the detailed calculation. As guidance to the design team, the analysis shows correctly where the largest contribution and thereby the potentially largest reduction potential lies, as the probabilistic calculation matches the detailed calculation without uncertainties. This tendency of concrete structures to be the main contributor of GWP confirms results from previous studies [55,56].

For PERT, the overall result differs by a maximum of +5% (simplified calculation) and +2% (probabilistic calculation), but contribution differs by up to –5% and +9%, changing the ranking of building parts. The detailed calculation indicates that the structure offers the largest reduction potential, whereas the probabilistic and simplified calculations suggest the internal walls as the largest contributor. The underlying reason for this is the fact that the probabilistic calculation uses one material, gypsum board, for the interior walls; whereas the interior of the as-built building consists of a mixture of different wall types, e.g., glass partitions or masonry walls. Gypsum board demands about 10 times more renewable energy pro volume (m^3) than masonry (2167 MJ vs. 263 MJ) but shows only roughly three times as much GWP. Hence, for a building part with an inhomogeneous mix of materials, the simplification to just one material can have a large influence on results. For building parts with fewer materials, like the building's structure, where the bulk of the building part is made of one material, the probabilistic calculation should render accurate indications of their relevance within the building.

4. Discussion

Our results highlight the possibility of real-time life cycle analysis in early stages of design. Although the early stage analysis tends to underestimate the absolute values for PE demand and GHG emissions, valuable advice can be provided in two ways. First, the sensitivity analysis guides the designer towards the input parameters whose uncertainty causes the highest result uncertainties. Second, a contribution analysis reveals the strategic building parts where the potential is largest to reduce emissions and energy consumption.

The design team can use the results of the sensitivity analysis to reduce result uncertainties systematically by reducing the vagueness of the most relevant input parameters during the design process. Although reducing vagueness is a natural part of the detailing process, in a regular design process the design team is not aware of the impact on the precision of environmental analysis if an input parameter is detailed. Our analysis provides guidance toward which parameter's uncertainty to reduce first to get a more precise indication of environmental impact. A previous study [21] showed that this method can also applied to the entire life cycle including operational energy consumption. Future work should add other criteria (such as cost) and take into account the multi-criterial nature of decision processes in building design.

The contribution analysis shows the building parts contributing most to PE demand and GHG emissions hence revealing their theoretical reduction potential. In order to determine the reduction that can be realized, alternative materials need to be tested. We provided an example of this by replacing the concrete structure by a wood structure where possible. To integrate this trial-and-error process into a design assistance tool, a database containing alternatives for different materials and building parts needs to replace our simplified database containing only fixed materials. Hollberg et al. [57] and Röck et al. [58] employ a component catalogue to address this challenge showing the realizable reduction potential.

The contribution analysis works well for homogenous building parts, such as the structure, and confirms results from previous studies. On the other hand, the contribution analysis tends to skew results when building parts with a multitude of materials, such as the building's interior, are concerned. One way to counteract this would be to subdivide the building into more parts but thereby losing the early design stage simplicity. In addition, this phenomenon relates to material uncertainties in early design stages, which were not included in this study, but are subject to current (e.g., Tecchio et al. [51]) and future research.

For our early stage analysis, we considered three indicators. This represents a simplification from all 23 indicators available in Oekobaudat. However, the analysis shows that strategically reducing uncertainties in parallel for all three indicators is unachievable because result uncertainty for each indicator is dependent on input uncertainty of different parameters. This was to be expected regarding non-renewable and renewable energy, as increasing the use of renewable energy sources reduces non-renewable PE demand, i.e., these two indicators should inversely correlate. It is somewhat surprising that GWP and PENRT do not correlate, as the burning of fossil fuels, i.e., the use of PENRT, causes GHG emissions. In part, the fact that the chemical process of clinker production in the cement production process emits CO_2 provides an explanation. For other materials than concrete, the reasons for the lack of correlation are less clear. Generally, this points to the fact that LCA results should not be reduced to one indicator, as none of the indicators can be regarded as representative for all others. Instead, decisions based on LCA results need to be treated as multi-criteria decisions.

To increase the completeness of results, more building materials will be implemented in our model. In order to achieve this, additional input parameters will have to be considered (e.g., concrete strength) and additional information (e.g., type of waterproofing) will have to be estimated. Additionally, the structural material types, reinforced concrete and wood, will be complemented by structural steel and hybrid structures. This has implications on the possible application of the method but does not change the methodological approach.

As shown in our previous work [21], LCA is incomplete if it neglects the operational phase. Therefore, we direct future research efforts towards integrating all life cycle phases, which implies also including the building's mechanical systems. We expect multiple interdependencies calling for a detailed sensitivity and contribution analysis in conjunction with a weighting system for results.

Author Contributions: Conceptualization, P.S.; Methodology, P.S. and H.H..; Software, H.H. and K.T.; Validation, P.S. and K.T.; Writing—Original Draft Preparation, P.S.; Writing—Review and Editing, H.H., W.L. and K.T.; Visualization, P.S.; Funding Acquisition, W.L. and P.S.

Funding: This research was funded by the German Research Foundation (Deutsche Forschungsgemeinschaft, DFG) under grant FOR2363—project number: 271444440.

Acknowledgments: We thank Ferdinand Tausendpfund GmbH & Co. KG for providing their office building as a sample project. Thank you also to our colleague Jimmy Abualdenien from the EarlyBIM project for the valuable input and discussions. Last, but not least, we would like to thank two anonymous reviewers for their valuable feedback.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A. Results of probabilistic calculation

Table A1. Sensitivities as shown in Figure 2.

BDL2					
	geo 10%	tech 25%	win 25%	int 25%	sum
'gwp'	0,48	0,48	0,02	0,04	1,01
'pert'	0,49	0,25	0,01	0,27	1,02
'penrt'	0,54	0,34	0,02	0,11	1,01
BDL3					
	geo 2%	tech 10%	win 25%	int 25%	sum
'gwp'	0,13	0,53	0,09	0,26	1,01
'pert'	0,06	0,12	0,01	0,83	1,02
'penrt'	0,11	0,27	0,09	0,54	1,01
BDL4					
	geo 1%	tech 5%	win 25%	int 10%	sum
'gwp'	0,11	0,46	0,30	0,14	1,01
'pert'	0,08	0,17	0,03	0,74	1,02
'penrt'	0,10	0,25	0,34	0,32	1,01

Table A2. Full results of probabilistic calculations for BDL 2, 3, and 4 and concrete and wood structure.

BDL 2 Concrete								
-	-	**Mean**	**Var**	**StD**	**%con**	**%ins**	**%win**	**%int**
'gwp'	'kgCO_2-Eq'	3,3924E + 05	3,5565E + 08	1,8859E + 04	49,81%	13,51%	22,77%	13,92%
'pert'	'MJ'	5,2745E + 05	1,1230E + 09	3,3511E + 04	36,68%	9,04%	11,02%	43,27%
'penrt'	'MJ'	3,6601E + 06	3,9457E + 10	1,9864E + 05	37,58%	14,57%	24,90%	22,94%
'pert+penrt'	MJ	4,1876E + 06	5,3446E + 10	2,3118E + 05	-	-	-	-
PENRT/PET	12,60%	-	-	-	-	-	-	-
BDL 2 Wood								
		Mean	**Var**	**StD**	**%con**	**%ins**	**%win**	**%int**
'gwp'	'kgCO_2-Eq'	2,5298E + 05	1,5306E + 08	1,2372E + 04	33,11%	18,00%	30,34%	18,55%
'pert'	'MJ'	1,1750E + 06	6,2815E + 09	7,9256E + 04	72,12%	3,98%	4,85%	19,05%
'penrt'	'MJ'	3,3117E + 06	2,7923E + 10	1,6710E + 05	31,72%	15,94%	27,24%	25,10%
'pert+penrt'	MJ	4,4867E + 06	5,7203E + 10	2,3917E + 05	-	-	-	-
PENRT/PET	26,19%	-	-	-	-	-	-	-
BDL 3 Concrete								
		Mean	**Var**	**StD**	**%con**	**%ins**	**%win**	**%int**
'gwp'	'kgCO_2-Eq'	3,3683E + 05	4,9952E + 07	7,0677E + 03	49,84%	13,44%	22,78%	13,94%
'pert'	'MJ'	5,1711E + 05	3,4538E + 08	1,8584E + 04	36,69%	8,99%	11,02%	43,30%
'penrt'	'MJ'	3,6196E + 06	7,4711E + 09	8,6436E + 05	37,60%	14,51%	24,92%	22,97%
'pert+penrt'	MJ	4,1367E + 06	1,0806E + 10	1,0395E + 05	-	-	-	-
PENRT/PET	12,50%	-	-	-	-	-	-	-
BDL 3 Wood								
		mean	**var**	**StD**	**%con**	**%ins**	**%win**	**%int**
'gwp'	'kgCO_2-Eq'	2,5271E + 05	2,8307E + 07	5,3204E + 03	33,14%	17,92%	30,37%	18,57%
'pert'	'MJ'	1,1745E + 06	9,7327E + 08	3,1197E + 04	72,13%	3,96%	4,85%	19,06%
'penrt'	'MJ'	3,3086E + 06	6,2364E + 09	7,8971E + 04	31,74%	15,87%	27,26%	25,13%

'pert+penrt'	MJ	4,4831E + 06	1,1056E + 10	1,0515E + 05	-	-	-	-
PENRT/PET	-	26,20%	-	-	-	-	-	-
BDL 4 Concrete								
		mean	**var**	**StD**	**%con**	**%ins**	**%win**	**%int**
'gwp'	'kgCO_2-Eq'	3,3679E + 05	1,4690E + 07	3,8328E + 03	49,84%	13,44%	22,79%	13,94%
'pert'	'MJ'	5,1709E + 05	6,2175E + 07	7,8851E + 03	36,69%	8,99%	11,02%	43,30%
'penrt'	'MJ'	3,6191E + 06	2,0592E + 09	4,5378E + 04	37,61%	14,50%	24,92%	22,97%
'pert+penrt'	MJ	4,1362E + 06	2,7302E + 09	5,2251E + 04	-	-	-	-
PENRT/PET	-	12,50%	-	-	-	-	-	-
BDL 4 Wood								
		mean	**var**	**StD**	**%con**	**%ins**	**%win**	**%int**
'gwp'	'kgCO_2-Eq'	2,5267E + 05	1,0625E + 07	3,2596E + 03	33,14%	17,91%	30,37%	18,58%
'pert'	'MJ'	1,1744E + 06	2,2059E + 08	1,4852E + 04	72,12%	3,96%	4,85%	19,07%
'penrt'	'MJ'	3,3082E + 06	1,8105E + 09	4,2550E + 04	31,74%	15,86%	27,27%	25,13%
'pert+penrt'	MJ	4,4826E + 06	2,7277E + 09	5,2227E + 04	-	-	-	-
PENRT/PET	-	26,20%	-	-	-	-	-	-

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