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Marco Scherz

Life cycle assessment-based procurement of buildings using the systemic know-why planning process

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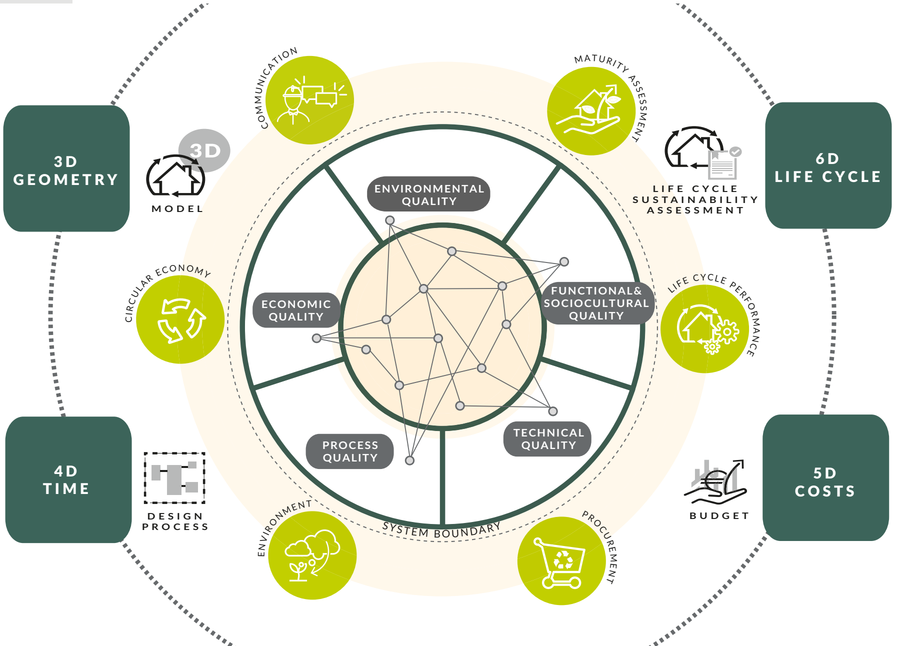

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This work is based on the dissertation *"Life cycle assessment-based procurement of buildings using the systemic know-why planning process"* presented by Marco Scherz at Graz University of Technology, Working Group Sustainable Construction, Institute of Structural Design in 2023.

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Preface

This doctoral thesis was completed through the Working Group Sustainable Construction at Graz University of Technology in Austria. The research for this doctoral thesis was carried out between 2018 and 2023 under the supervision of Univ.-Prof. Dipl.-Ing. Dr.techn. Alexander Passer, MSc and the cosupervision of Dipl.-Ing. Dr.techn. Helmuth Kreiner. This doctoral thesis has been submitted to the Faculty of Civil Engineering of the Doctoral Programme in Technical Sciences.

This doctoral thesis is based on five thesis publications (thesis publications 1-5). I have been the first author of these publications, and all of them have been published in science citation indexed (SCI) journals as needed by the Doctoral Programme in Technical Sciences curriculum.

It must be acknowledged that I did not work in isolation when conducting my research or writing the five thesis publications.
As supervisor of this doctoral thesis, Univ.-Prof. Dipl.-Ing. Dr.techn. **Alexander Passer**, MSc had a decisive influence on the focus of each of these publications. Particularly regarding thesis publications 2, 3 and 4, he provided comprehensive feedback on the application and implementation of life cycle assessment (LCA).
Dipl.-Ing. Dr.techn. **Helmuth Kreiner** played a leading role as my cosupervisor and mentor for the five thesis publications. In particular, he contributed to the theoretical and conceptual aspects of thesis publications 2, 3 and 5. Furthermore, he validated all thesis publications, which were continuously improved by his feedback.

Nicolas Bernard Jean Alaux contributed to writing the introduction and the incorporation of the revisions of thesis publication 4. **Endrit Hoxha** supported thesis publication 3 by recalculating the LCA results. Furthermore, he supported me in the conceptual preparation of thesis publication 5. **Dominik Maierhofer** provided the figures for thesis publication 3 and supported me with proofreading. **Amin Vafadarnikjoo** contributed to the conceptual design of thesis publication 5 and authored the methods section on hierarchical decision making (HDM). **Antonija Ana Wieser** assisted me in preparing the systematic literature review (SLR) of thesis publication 1 and contributed to the writing process for that work, particularly in summarizing the metadata of the SLR.

The full texts of the five thesis publications are attached to Appendix A.

Thesis publications

1. **Scherz, M.**, Wieser, A.A., Passer, A. & Kreiner, H. (2022). **Implementation of Life Cycle Assessment (LCA) in the Procurement Process of Buildings: A Systematic Literature Review.** *Sustainability 14*. https://doi.org/10.3390/su142416967

2. **Scherz, M.**, Kreiner, H. & Passer, A. (2023). **Sustainable procurement for carbon neutrality of buildings: a Life Cycle Assessment (LCA)-based bonus/malus system to consider external cost in the bid price.** *Developments in the Built Environment 14*. https://doi.org/10.1016/j.dibe.2023.100161

3. **Scherz, M.**, Hoxha, E., Maierhofer, D., Kreiner, H. & Passer, A. (2022). **Strategies to improve building environmental and economic performance: An exploratory study on 37 residential building scenarios.** *The International Journal of Life Cycle Assessment*. https://doi.org/10.1007/s11367-022-02073-6

4. **Scherz, M.**, Kreiner, H., Alaux, N. & Passer, A. (2023). **Transition of the procurement process to Paris-compatible buildings: consideration of environmental life cycle costing in tendering and awarding.** *The International Journal of Life Cycle Assessment*. https://doi.org/10.1007/s11367-023-02153-1

5. **Scherz, M.**, Hoxha, E., Kreiner, H., Passer, A. & Vafadarnikjoo, A. (2022). **A Hierarchical Reference-Based Know-Why Model for Design Support of Sustainable Building Envelopes.** *Automation in Construction 139*. https://doi.org/10.1016/j.autcon.2022.104276

Additionally, during my time as a scientific assistant and PhD candidate at the Working Group Sustainable Construction, I have authored or coauthored additional peer-reviewed publications, conference articles and book chapters that relate to my doctoral thesis. Due to their relevance for this doctoral thesis, the abstracts of four additional thesis publications are attached to Appendix B.

Additional thesis publications

1. Kreiner, H., **Scherz, M.** & Passer, A. (2018). **How to make decision-makers aware of sustainable construction?** In R. Caspeele, L. Taerwe, & D. Frangopol (Eds.), *Life-Cycle Analysis and Assessment in Civil Engineering: Towards an Integrated Vision - Proceedings of the 6th International Symposium on Life-Cycle Civil Engineering, IALCCE 2018*. `https://www.taylorfrancis.com/chapters/edit/10.1201/9781315228914-58/make-decision-makers-aware-sustainable-construction-kreiner-scherz-passer`

2. **Scherz, M.**, Zunk, B.M., Passer, A. & Kreiner, H. (2018). **Visualizing interdependencies among sustainability criteria to support multicriteria decision-making processes in building design.** *Procedia CIRP 69.* `https://doi.org/10.1016/j.procir.2017.11.115`

3. **Scherz, M.**, Passer, A. & Kreiner, H. (2020). **Challenges in the achievement of a Net Zero Carbon Built Environment – A systemic approach to support the decision-aiding process in the design stage of buildings.** *IOP Conference Series: Earth and Environmental Science 588*. `https://doi.org/10.1088/1755-1315/588/3/032034`

4. **Scherz, M.**, Zunk, B.M., Steinmann, C. & Kreiner, H. (2022). **How to assess sustainable planning processes of buildings? A maturity assessment model approach for designers.** *Sustainability 14*. `https://doi.org/10.3390/su14052879`

Further scientific output

A summary list of all my other scientific outputs can be found in Appendix C.

Abstract

The building sector accounts for an enormous share of global greenhouse gas (GHG) emissions and, therefore, is also responsible for the continuing decrease in the remaining budget of GHG emissions. The latest European Union (EU) directive on public procurement proposes that building contracts should be awarded according to life cycle costing (LCC), considering environmental externalities.

In Austria, however, no feasible cost model, which considers the environmental quality of buildings when awarding contracts, has yet been developed for the building procurement process.

The objective of the dissertation is the development of a cost model for the procurement of buildings that enables mandatory applications of life cycle assessment (LCA) in the future and considers the environmental quality of buildings in the award decision. Furthermore, the objective is the development of a systemic planning approach that supports the implementation of a future LCA-optimized planning process for a more environmentally friendly procurement of buildings.

The environmental life cycle costing (eLCC) method monetizes building-related GHG emissions, i.e. embodied and operational GHG emissions, and integrates them as external costs into the bid prices of submitted bids. In addition, a GHG emissions bonus/malus is determined to calculate Paris-compatible cost (PCC) scenarios that are used as award criteria in the building procurement process. By combining the know-why method and the building certification system of the German Sustainable Building Council, a systemic planning process model is developed. With the application of the process model, interactions among planning measures, i.e. synergies and trade-offs, can be identified and impacts on project goals, such as optimized environmental building quality or other sustainability aspects, can be analysed.

The dissertation fills the research gap of a missing cost model for a more environmentally friendly building procurement process in Austria. The results show that by implementing the LCA-based bonus/malus system in contrast to conventional building procurement processes, i.e. based on the awarding according to the lowest price, the procurement of planning alternatives with a higher environmental quality is promoted. In addition, it has been shown that the requirements for an LCA-optimized planning process are managed with the application of the hierarchical reference-based know-why model, thus, reducing project-specific undesirable developments in terms of quality, time and costs at an early stage.

By developing the presented models, the LCA-based bonus/malus system for the building procurement process and the hierarchical reference-based know-why model for the planning process, the basis for further implementation steps of a more environmentally friendly building procurement process in Austria was laid. By applying the models to all building procurement processes, the greatest possible potential for the reduction of GHG emissions can be exploited, thus, making a significant contribution to achieving climate targets.

Kurzfassung

Der Gebäudesektor hat einen enormen Anteil an den weltweiten Treibhausgasemissionen (THG-Emissionen) und ist daher auch für den anhaltenden Rückgang des verbleibenden THG-Budgets verantwortlich. Die jüngste Richtlinie der Europäischen Union (EU) über das öffentliche Beschaffungswesen schlägt vor, dass Aufträge für die Beschaffung von Gebäuden auf der Grundlage der Lebenszykluskostenrechnung (engl. life cycle costing, LCC) unter der Berücksichtigung externer Umweltauswirkungen vergeben werden sollen.

In Österreich fehlt jedoch ein adäquates Kostenmodell für den Gebäudebeschaffungsprozess, welches die umweltbezogene Qualität von Gebäuden bei der Vergabe berücksichtigt.

Ziel der Dissertation ist es, ein Kostenmodell für die Beschaffung von Gebäuden zu entwickeln, welches künftig eine verpflichtende Anwendung der Ökobilanz (engl. life cycle assessment, LCA) ermöglicht und die umweltbezogene Qualität von Gebäuden bei der Vergabeentscheidung berücksichtigt. Weiters soll ein systemischer Planungsansatz entwickelt werden, um die Implementierung eines zukünftigen LCA-optimierten Planungsprozesses für eine ökologischere Gebäudebeschaffung zu unterstützen.

Mit der Methode der ökologischen Lebenszykluskostenrechnung (engl. environmental life cycle costing, eLCC) werden gebäudebezogene THG-Emissionen, d.h. graue und betriebliche THG-Emissionen, monetarisiert und in Form von externen Kosten in die Angebotspreise von abgegebenen Angeboten integriert. Zusätzlich wird ein THG-Emissions-Bonus/Malus ermittelt, um Paris-kompatible (engl. Paris-compatible cost, PCC) Kostenszenarien zu berechnen, die als Vergabekriterium im Gebäudebeschaffungsprozess herangezogen werden.

Durch die Kombination der Know-Why-Methode und des Gebäudezertifizierungssystems der Deutschen Gesellschaft für Nachhaltiges Bauen (DGNB) wird ein systemisches Planungsprozessmodell entwickelt. Mit der Anwendung des Prozessmodells können Wechselwirkungen zwischen Planungsmaßnahmen, d.h. Synergien und Zielkonflikte, identifiziert und Auswirkungen auf Projektziele, wie z.B. optimierte umweltbezogene Gebäudequalität oder andere Nachhaltigkeitsaspekte, analysiert werden.

Die Dissertation schließt die Forschungslücke eines fehlenden Kostenmodells für einen ökologischeren Gebäudebeschaffungsprozess in Österreich. Die Ergebnisse zeigen, dass durch die Implementierung des THG-Emissions-Bonus/Malus-Systems im Gegensatz zur herkömmlichen Gebäudebeschaffung, d.h. basierend auf dem Billigstbieterprinzip, die Beschaffung von Planungsalter-

nativen mit einer höheren umweltbezogenen Qualität gefördert wird.

Zusätzlich hat sich gezeigt, dass die Anforderungen an einen LCA-optimierten Planungsprozess mit der Anwendung des hierarchischen, referenzbasierten Know-Why-Modells bewältigt werden und somit projektspezifische Fehlentwicklungen hinsichtlich Qualität, Zeit und Kosten frühzeitig reduziert werden.

Durch die Entwicklung der vorgestellten Modelle, das THG-Emissions-Bonus/Malus-System für den Gebäudebeschaffungsprozess und das hierarchische, referenzbasierte Know-Why-Modell für den Planungsprozess, wurden die Grundlagen für weitere Umsetzungsschritte eines ökologischeren Gebäudebeschaffungsprozesses in Österreich geschaffen. Durch die Anwendung der Modelle auf alle Gebäudebeschaffungsprozesse kann das größtmögliche Potenzial zur THG-Emissionsreduktion ausgeschöpft werden und damit ein wesentlicher Beitrag zur Erreichung der Klimaziele geleistet werden.

Acknowledgements

Thank you to my supervisor, Alexander Passer from Graz University of Technology, for his support and advice during the completion of this doctoral thesis. Special thanks to my cosupervisor and mentor, Helmuth Kreiner from Graz University of Technology, for the excellent collaboration on numerous research projects and the steady, ongoing support and supervision of this doctoral thesis.

Thank you to my external reviewer, Alexander Hollberg from Chalmers University of Technology, for his valuable feedback and input during the review process, which further improved this doctoral thesis from a scientific and content perspective.

Thank you to my coauthors, Nicolas Bernard Jean Alaux, Endrit Hoxha, Helmuth Kreiner, Dominik Maierhofer, Alexander Passer, Christian Steinmann, Amin Vafadarnikjoo, Antonija Ana Wieser and Bernd Markus Zunk, who supported my research with fruitful discussions, advice and guidance.

Thank you to all of my colleagues in the Working Group Sustainable Construction who have supported me with valuable research-related and personal conversations and have always contributed to a productive working atmosphere.

Thank you to Graz University of Technology for the opportunity to work as a scientific assistant and in the field of research and development. Without such employment, the completion of this doctoral thesis would not have been possible.

Thank you to the funding organizations for enabling research on various subjects and, thus, supporting the development of thesis-relevant results and publications. Thank you to Zukunftsfonds Steiermark for funding the project *Sustainable Design Process & Integrated Facades*. Thank you to the Alliance of Sustainable Universities in Austria and the Austrian Federal Ministry of Education, Science and Research for supporting the project *UniNEtZ - Universities and Sustainable Development Goals*. Thank you to the Climate and Energy Fund for funding the project *Paris Buildings - Transition of the Procurement Process Towards Paris-Compatible Public Buildings*.

Thank you to my parents, Anita and Peter, and to my sister, Nadine, for the great childhood and the opportunity to pursue my educational path and complete this doctoral thesis. Thank you for the many years of support and love.

Glossary

AHP analytic hierarchy process
AI artificial intelligence
BIG Bundesim- mobiliengesellschaft
BIM building information modelling
BKI building cost index (German: Baukostenindex)
BNB assesment system for sustainable buildings (German: Bewertungssystem Nachhaltiges Bauen)
CCCA Climate Change Center Austria
CEN European Committee for Standardization (French: Comité Européen de Normalization)
CE circular economy
cLCC conventional life cycle costing
DGNB German Sustainable Building Council (German: Deutsche Gesellschaft für Nachhaltiges Bauen)
EPBD energy performance of buildings directive
EPDs environmental product declarations
EC European Commission
eLCC environmental life cycle costing
EU European Union
ETSs emissions trading systems
GBG Gebäude- und Baumanagement Graz GmbH
GABC Global Alliance for Buildings and Construction
GHG greenhouse gas
GWP global warming potential
HDM hierarchical decision making
IEA International Energy Agency
IPCC Intergovernmental Panel on Climate Change
ISO International Organization for Standardization
LCA life cycle assessment
LCC life cycle costing
LCSA life cycle sustainability assessment
LIG Landesimmobiliengesellschaft Steiermark
MCDM multicriteria decision making
MEAT most economically advantageous tender
MIT Massachusetts Institute of Technology
naBe action plan for sustainable public procurement (German: Aktionsplan nachhaltige öffentliche Beschaffung)

NEKP national energy and climate plan (German: Nationaler Energie- und Klimaplan)

NFA net floor area

NPV net present value

ÖGNB Austrian Sustainable Building Council (German: Österreichische Gesellschaft für Nachhaltiges Bauen)

ÖGNI Austrian Sustainable Building Council (German: Österreichische Gesellschaft für Nachhaltige Immobilienwirtschaft)

OIB Austrian Institute of Construction Engineering (German: Österreichisches Institut für Bautechnik)

PRISMA preferred reporting items for systematic reviews and meta-analyses

PCC Paris-compatible cost

RBCF results-based climate finance

RSP reference study period

SCI science citation indexed

SDGs Sustainable Development Goals

SETAC Society of Environmental Toxicology and Chemistry

sLCA social life cycle assessment

sLCC societal life cycle costing

SLR systematic literature review

TC technical committee

TQB total quality building

UN United Nations

WGBC World Green Building Council

WLC whole life costing

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1 Introduction

In recent decades, the Earth's natural systems have been placed under increasing pressure due to human activities, leading to concerns over the stability of our planet. To address these concerns, the concept of planetary boundaries was introduced in 2009 by Rockström et al. [1].

Within the concept of planetary boundaries, nine critical Earth system processes that regulate the stability and resilience of the planet are identified and quantified. These processes, when pushed beyond their limits, can lead to irreversible and abrupt environmental changes that carry severe consequences for human well-being. In addition to one of the most pressing challenges, i.e. climate change, the planetary boundaries framework also highlights other critical boundaries, such as biodiversity loss, land use change, freshwater use, and ocean acidification [2].

Climate change, which is caused by human activities, such as burning fossil fuels and deforestation, traps heat in the Earth's atmosphere, leading to an increase in global temperatures and the prevalence of disruptive weather patterns. The effects of progressive climate change on our planet and, thus, society are becoming noticeably stronger. The increasing prevalence of extreme weather events, such as storms, floods, heat waves and droughts, is not only causing great economic damage but also increasingly claiming human lives, which will continue in the future [3, 4, 5].

The planetary boundary framework, by prioritizing the necessity of staying within Earth's safe operating limits, is closely linked to the concept of strong sustainability, which emphasizes that natural resources and ecosystems are one-of-a-kind and cannot be replaced by human-made alternatives [6].

In contrast, weak sustainability reflects the view that natural capital and human-made capital are somewhat interchangeable. Supporters of the weak sustainability concept argue that economic growth can persist even if certain environmental resources are depleted or damaged as long as investments are made in human-made alternatives that offset these losses [7].

Building on previous efforts towards sustainable development advocated through the Brundtland Report [8], the Rio Declaration [9], the Kyoto Protocol [10] and the Millennium Development Goals [11], the 2030 Agenda for Sustainable Development is one of the latest frameworks for measuring and monitoring various sustainability aspects that occur in the two concepts of sustainability and within planetary boundaries [12, 13].

The Sustainable Development Goals (SDGs) are a set of global objectives designed by the United Nations (UN) to tackle social, economic, and environmental challenges. One important aspect of the SDGs is their recognition that the well-being of humanity and the health of the planet are closely interconnected. To track the progress made towards these goals, the SDGs include indicators that specifically relate to planetary boundaries. These indicators help measure key environmental areas, such as greenhouse gas (GHG) emissions[1], biodiversity loss, land degradation, water scarcity, and pollution levels. By including these indicators, the SDGs provide a comprehensive framework for assessing and managing human activities in a way that respects our planet's limits and does not cross critical planetary boundaries [15].

The construction industry influences many of the 17 SDGs and, therefore, also the nine critical Earth system processes that occur within the planetary boundaries [16, 17]. Notable areas include the influences on SDGs related to affordable and clean energy (SDG 7) in terms of energy sources and energy consumption in the use phase of buildings, to sustainable cities and communities (SDG 11) in terms of more resilient cities with high resource and energy efficiency, to responsible consumption and sustainable production (SDG 12) associated with the building materials used and their lifespan in the context of the circular economy (CE), to climate protection (SDG 13) regarding to the emitted GHG emissions over the entire life cycle of buildings (embodied emissions and operational emissions), and to life on land (SDG 15) in relation to the additional land use of new buildings [18].

Due to the importance of the building sector to the achievement of climate goals, in recent decades, the principles of sustainable development have been increasingly researched and applied in both theory and practice. Accordingly, buildings must be planned, constructed, operated and holistically deconstructed in a life cycle-oriented manner so that the building stock represents an asset for future generations and is not simply a decaying legacy [19].

Sustainable construction is particularly important in the building sector because of the long life cycle of buildings, which can span decades or even centuries. In addition to the environmental, economic, sociocultural and functional, technical and process-related significance of sustainable construction, its implementation plays an important role in other areas, particularly in the context of reducing GHG emissions, due to the high material and energy flows generated by the building sector [20].

For the performance assessment of individual building materials, building elements or entire buildings, methods of life cycle sustainability assessment (LCSA) have been established [21].

In addition to LCSA, at the building level, numerous other sustainability assessment frameworks, such as building certification systems, have been established in the last three decades [22, 23, 24], resulting in approximately 600

[1]This doctoral thesis distinguishes between embodied and operational greenhouse gas emissions. The sum of these emissions is known as whole life carbon (WLC) [14].

available assessment methods. The scope of the areas addressed by these methods is diverse, ranging from a single area, such as energy efficiency, to a wide range of areas belonging to all three pillars of sustainability, i.e. environmental, economic and societal [25].

For the assessment of environmental performance, the method of LCA, which is also used for the creation of environmental product declarations (EPDs), is the most applied [26, 27, 28]. Regarding economic performance, the life cycle costing (LCC) method is one of the most commonly used to assess buildings [29, 30].

Many of these assessment methods, e.g. building certification systems, such as the German Sustainable Building Council (German: Deutsche Gesellschaft für Nachhaltiges Bauen) (DGNB) building certification system developed by the DGNB, already account for the SDGs and thus also reflect the nine Earth system processes that occur within the planetary boundaries [31].

One of the drivers of this increasingly global problem is the growing emission level of anthropogenic GHG. According to an Intergovernmental Panel on Climate Change (IPCC) status report, global net anthropogenic GHG emissions in 2019 were 54 percent higher than those in 1990 and approximately 12 percent higher than those in 2010. All major groups of GHG emissions increased, with GHG emissions from fossil fuels and industry showing the largest increase at approximately 67 percent higher than that in 1990 [32].

This increasing trend is evident across all major sectors (e.g. energy supply sector; industry, agriculture, forestry and other land use; transport; and construction). Especially regarding climate change, buildings contribute to exceeding planetary limits due to their enormous amounts of GHG emissions. In the annual status reports published by UN Environment, the International Energy Agency (IEA) and the Global Alliance for Buildings and Construction (GABC), buildings and their operations account for 37 percent of global energy consumption and approximately 40 percent of energy-related GHG emissions [33].

1.1 Objectives

The greatest opportunity to influence the environmental performance of buildings is in the early building project phase [34, 35].

While the design and realization of sustainable construction lies within the sphere of influence of architects and planners, an even more decisive lever, i.e. the tendering and awarding process for buildings, lies within the sphere of influence of the awarding authorities. By using its purchasing power to select environmentally friendly goods, services and construction, public administration can make an important contribution to sustainable consumption and production within the building sector.

As a result, public procurement principles for buildings have also advanced to meet the requirements of sustainable development. Since 2004, this progress has been anchored in European Union (EU) directives 2004/17/EC and 2004/18/EC, which stipulate that contracts can be awarded on the basis of the most economically advantageous tender (MEAT) in addition to the lowest price [36, 37].

In 2014, EU directive 2014/24/EU even referred to awarding based on LCC and the monetary consideration of environmental externalities. To calculate environmental externalities, the LCA method is suggested [38].

If the public sector, including entities such as municipalities, city councils and federal governments, tender and award buildings in a sustainable manner, which implies making LCA mandatory during the tendering and awarding process, a significant contribution towards GHG emissions reduction can be made. However, the mandatory implementation of LCA in the tendering and awarding process is currently neither a legally binding nor generally accepted practice.

Therefore, this doctoral thesis has two main objectives. The first is the development of a cost model for procurement that allows for the future mandatory application of LCA and accounts for the environmental performance of buildings in the award decision. The second is the development of a planning approach that ensures the implementation of a modified procurement process in the future and supports managing the additional requirements.

Figure 1.1 shows the application of the two objectives of this doctoral thesis in the five building project phases[1].

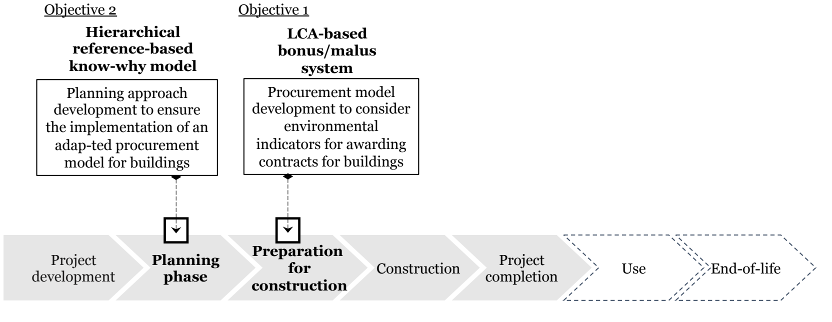


Figure 1.1: Application of the main objectives to the building project phases.

[1]Five building project phases according to the fee schedule for project management [39] extended by the life cycle phases of use and end-of-life.

1.2 Hypothesis and research questions

The successful application of life cycle assessment (LCA) in the tendering and awarding process for buildings can contribute to greenhouse gas (GHG) emissions reduction within the building sector. This reduction can be achieved through the implementation of a new cost model in the tendering and awarding process for buildings that considers the monetization of environmental indicators. The additional requirements that arise in future LCA-optimized planning can be managed through a systemic planning process.

To verify or disprove the hypothesis, the main research question of this doctoral thesis is defined as follows:

How should monetized environmental indicators be implemented in the tendering and awarding process for buildings?

The main research question is further divided into four subresearch questions:

1. What are the key barriers and challenges hindering the successful implementation of LCA in the tendering and awarding process for buildings?
2. What specific procedural steps are needed to effectively implement monetized environmental indicators in the tendering and awarding process for buildings?
3. How do carbon pricing instruments impact the award decisions for buildings?
4. How should the planning process of buildings be modified to effectively address the future demands of LCA-optimized planning?

1.3 Structure and research framework

This doctoral thesis is classified as a "mantel" doctoral thesis and consists of a summary of five thesis publications.

Figure 1.2 illustrates the structure of this doctoral thesis and shows the contents of the five chapters.

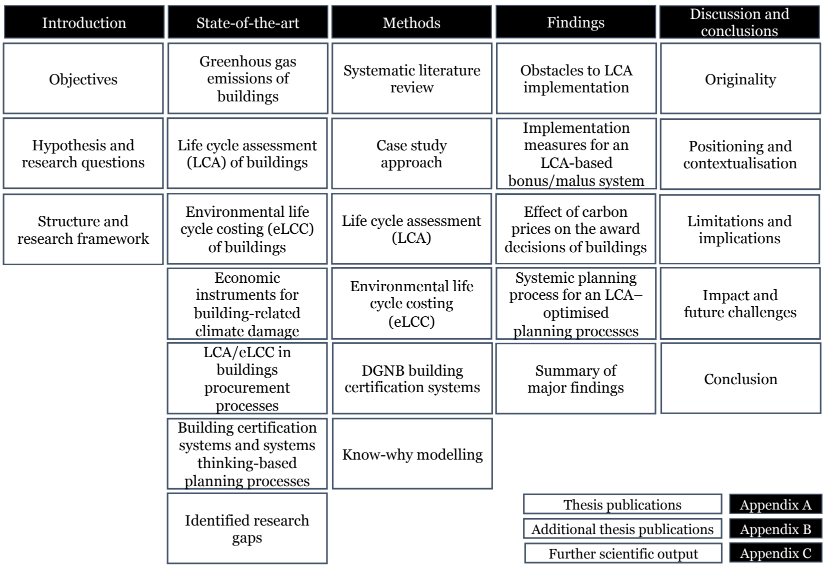


Figure 1.2: Structure and content of this doctoral thesis.

The research framework of this doctoral thesis is based on the so-called hypothetical deductive approach. The hypothetical deductive approach is a scientific method used to formulate and test hypotheses to improve the knowledge and understanding in various fields. The approach consists of several steps that are systematically carried out [40].

Based on the defined research questions, the first step is to formulate a hypothesis, which is a testable prediction or explanation based on previous knowledge and existing theories or observations. Hypothesis formulation is followed by the planning and execution of empirical tests or experiments to collect data or evidence. This involves the use of systematic observations, experiments, or surveys to test and validate the hypothesis. Importantly, that the operationalization, i.e. the definition of terms, data collection and selection of research methods and instruments, must be carefully planned out. The collected data, i.e. the sample, are investigated and evaluated in the next step. Statistical methods and other analytical techniques are used to evaluate the relationships among the variables and draw meaningful conclusions from the data.

The interpretation of the results is aimed at analysing the data to identify their patterns, trends, and relationships. This approach allows for a more comprehensive interpretation of the results and contributes to the discovery of knowledge. After validating the findings, conclusions are drawn from the results, and the hypothesis is either verified or disproven. If appropriate, the original hypothesis is refined or revised based on the obtained results [41].

The steps from sampling to validation are processed using the hermeneutic cycle approach. The hermeneutic cycle is a methodological approach used in interpretive research to analyse and understand complex textual or qualitative data. The hermeneutic cycle begins from an existing understanding and moves through analytical and empirical investigations; an expansion of knowledge unfolds as a deductive process, which is the basis for an adapted preunderstanding and simultaneously serves as the starting point for the next phase of knowledge expansion [42].

Figure 1.3 illustrates the combination of the hypothetical deductive approach and the hermeneutic cycle within the research framework.

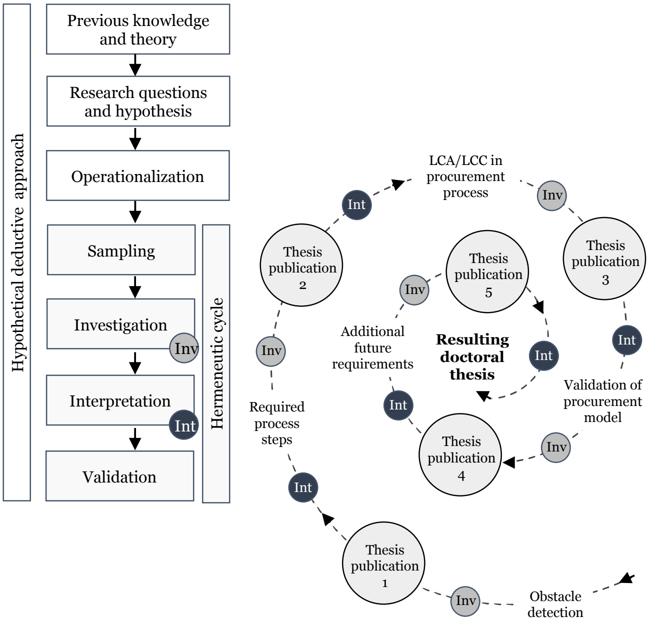


Figure 1.3: Combining the hypothetical deductive approach and the hermeneutic cycle within the research framework.

Within the hermeneutic cycle, first, an initial examination of the text or data occurs with the aim of becoming familiar with the material and gaining an initial understanding of the content and context represented by the data. Following the identification and analysis of key themes, symbols, or patterns in the text, various elements that emerge from the data are examined regarding their relevance to the research questions or objectives. The next step is the interpretation of the results and meaning-making from the insights gained through critical analysis of the text and the use of previous knowledge, theoretical frameworks, and cultural perspectives. Different interpretations may arise, raising further questions, and the hermeneutic process is repeated [42].

In summary, the objectives of this doctoral thesis are, first, the development of a new methodological procedure, the so-called LCA-based bonus/malus system, for the implementation of monetized environmental aspects, i.e. GHG emissions, in the tendering and awarding process for buildings. Second, the thesis is meant to provide an adapted systemic planning process for managing the additional complex requirements caused by the newly developed procurement procedure.

Figure 1.4 illustrates the spheres of influence of the LCA-based bonus/malus system and the hierarchical reference-based know-why model within the building project phases[1]. In addition, the five thesis publications, the four additional thesis publications and the underlying methods are each assigned to one of the two developed models.

[1]Five building project phases according to the fee schedule for project management [39] extended by the life cycle phases of use and end-of-life.

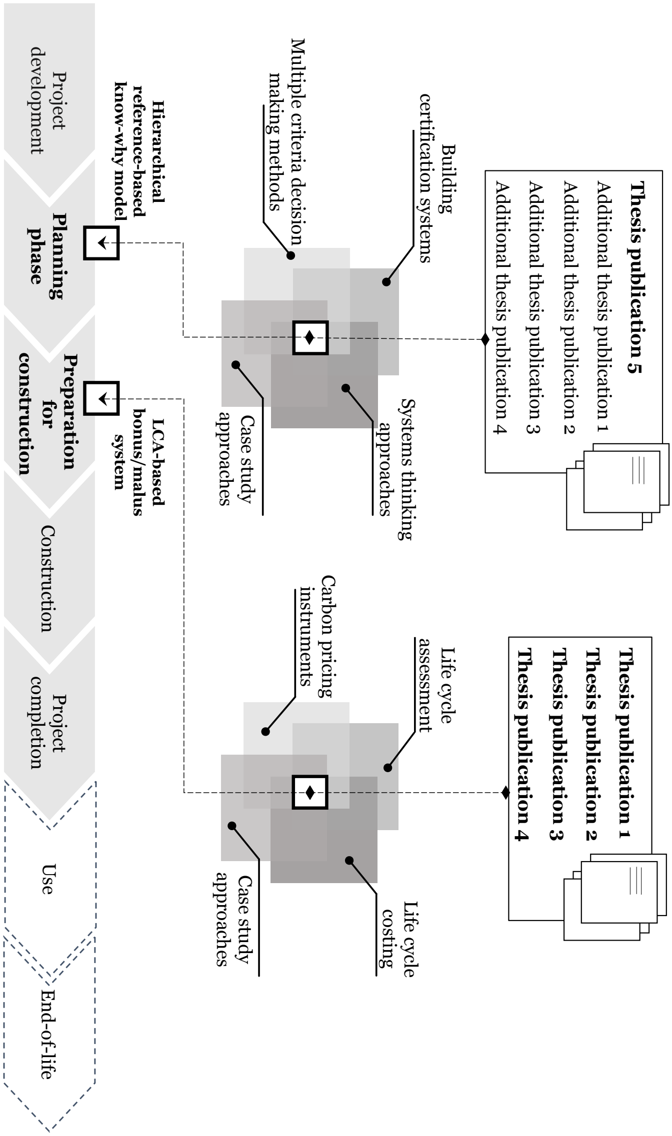


Figure 1.4: Impact of this doctoral thesis in each of the building project phases highlighting the main thesis publications, the additional thesis publications, and the applied methods.

2 State-of-the-art

Driven by the Paris Agreement, the European Commission (EC) is pursuing the goal of Europe becoming the world's first climate-neutral continent by 2050 [43].

With the presentation of the European Green Deal, a milestone was set for this purpose; thus, the new growth strategy of the EU was established. The transformation of the EU economy for a sustainable future is meant to be achieved by meeting the following goals, among others [44]:

- meeting ambitious EU climate protection targets for 2030 and 2050;
- securing a supply of clean, affordable and secure energy;
- mobilizing industry for a clean and CE;
- ensuring energy- and resource-efficient construction and renovation;
- meeting a zero-pollutant goal for a pollution-free environment;
- preserving and restoring ecosystems and biodiversity;
- creating a fair, healthy and environmentally friendly food system;
- accelerating the shift to sustainable and intelligent mobility.

This has prompted the EC to introduce a voluntary EU Level(s) reporting framework with the aim of establishing a standardized approach for assessing the environmental performance of buildings. The Level(s) framework addresses six core indicators, namely, carbon emissions, materials, water use, health, climate change, and value and risk, developed to improve the environmental performance of buildings over their life cycle. Therefore, the EU Level(s) framework provides metrics for the following six macro objectives that will help future-proof building projects at all stages in line with CE, whole life carbon performance and other green policy goals [45]:

- evaluating GHG emissions throughout the building's life cycle;
- analysing the life cycle of materials to extend their use and reduce waste;
- improving water use efficiency;
- promoting healthy and comfortable spaces;
- increasing climate change adaptation and resilience;
- considering LCC and value over time.

Consequently, in parallel with the developments on the legislative side, numerous developments on the normative level by the European Committee for Standardization (French: Comité Européen de Normalization) (CEN)/technical committee (TC) 350 also exist from developing and providing standards for evaluating the environmental performance of buildings. In environmental building assessments, especially assessment of building-related GHG emissions, a distinction is made between embodied and operational GHG emissions. An overview of the work of CEN/TC 350 can be found in [46].

Figure 2.1 shows recent developments in building life cycle stages theory [47].

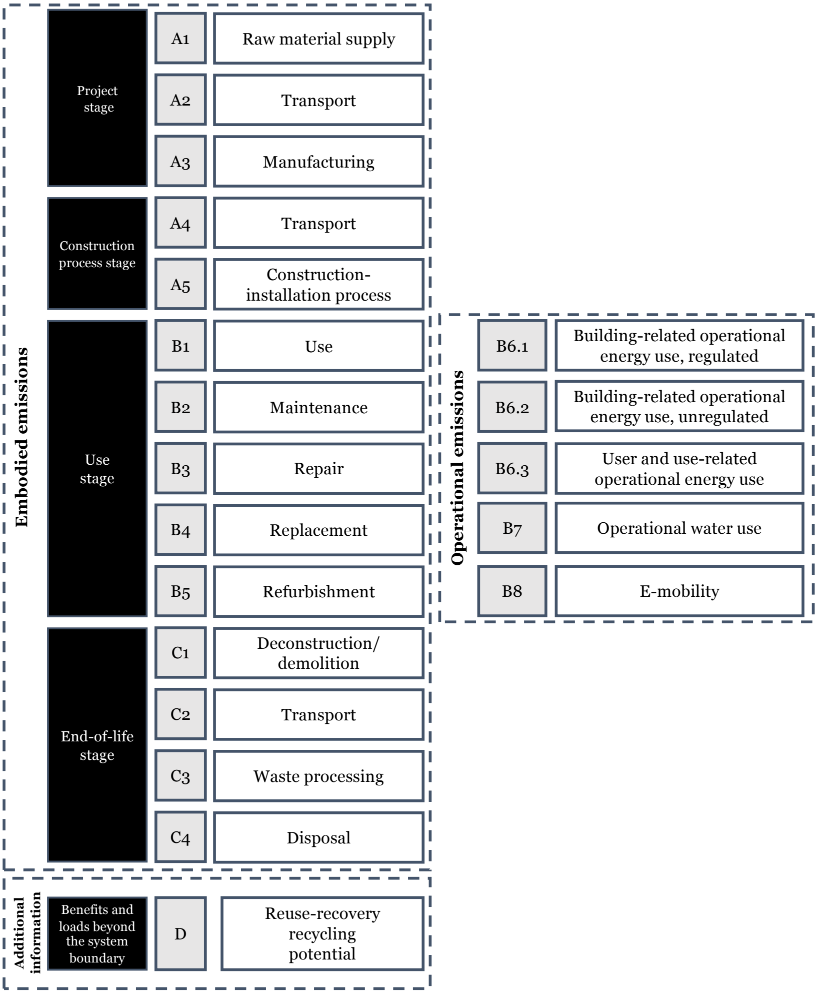


Figure 2.1: Building life cycle stages according to CEN/TC 350 [47].

In this context, building-related operational energy use and, thus, the emitted operational GHG emissions are addressed with the energy performance of buildings directive (EPBD).

The establishment of the EPBD was a significant achievement for energy efficiency in the field of sustainable construction. Initially, introduced by the EU in 2002, the EPBD was meant to create a common framework for improving the energy performance of buildings within EU member states [48].

The EPBD first introduced the energy performance certificate and defined minimum energy performance requirements for new buildings and renovations. Over the years, the EPBD has undergone several revisions to reflect the evolving understanding of energy efficiency and the need for more ambitious targets. Directive 2010/31/EU, also known as the recast, builds on EPBD of 2002 and strives to further improve the energy performance of buildings. While the focus is still principally maintained on the energy performance of buildings, the EPBD 2010 also recognizes the importance of accounting for the energy consumption that occurs during construction and renovation [49].

In 2018, the EPBD received a comprehensive update that introduced significant changes for improving the energy efficiency of buildings. Noteworthy additions included a requirement for EU member states to develop long-term renovation strategies for existing buildings with a focus on achieving highly energy-efficient and decarbonized building stock by 2050 [50].

Moreover, embodied GHG emissions were recently integrated into the amendments of the new EPBD. The strategy within the latest EPBD is aimed at progressively accounting for the life cycle emissions of buildings in accordance with a harmonized EU methodology. For both new buildings and renovations, the level of GHG emissions should be reduced throughout the entire life cycle. Emphasis is placed on calculating the life cycle global warming potential (GWP) of buildings to assess their contribution to climate change because doing so combines the embodied GHG emissions in building products with direct and indirect emissions from the use phase (operational emissions). Therefore, the requirement of calculating the GWP value of new buildings is a first step towards a greater consideration of the LCA of buildings and a CE [51].

Additionally, on the international, national and regional policy levels, the concern is growing that GHG emissions urgently need to be reduced to curb the global temperature rise. This position is also held by the EC, which has defined binding strategies in its 2030 Climate Target Plan and a 2050 long-term strategy for achieving these goals [52, 53].

In this context, the first European climate law was proposed in 2020 to legally anchor the climate neutrality target for 2050 [54]. These regulations became legally binding in 2021. As a result, EU member states are required to develop long-term national strategies to reduce GHG emissions to meet the Paris Agreement targets and EU climate targets [55].

In Austria, the integrated national energy and climate plan (German: Nationaler Energie- und Klimaplan) (NEKP) was recently sent out for public consultation by the Federal Ministry for Climate Protection, Environment, Energy, Mobility, Innovation and Technology to solicit feedback from the scientific community and other stakeholders [56].

Moreover, the content of the EPBD is implemented through the Austrian Institute of Construction Engineering (German: Österreichisches Institut für Bautechnik) (OIB) guidelines [57]. Regarding sustainable construction, OIB guideline 7, which concerns the implementation of basic requirement 7 of the construction product regulation titled the 'sustainable use of natural resources', is currently under development. Recently, a basic document describing OIB guideline 7 was published [58]. OIB guideline 7 itself will be published in 2027.

Another international step was the introduction of the EU taxonomy, officially known as the 'Regulation on the establishment of a framework to facilitate sustainable investment' (Regulation (EU) 2020/852). The EU taxonomy is an important tool for the EU to promote sustainability and combat climate change and creates a framework for the establishment of an EU-wide taxonomy for sustainable economic activities [59].

2.1 Greenhouse gas emissions of buildings

The remaining global GHG budget for achieving no interim temperature increase is approximately 820 $GtCO_2$eq and has a 50 percent probability of achieving the +1.5 degree Celsius temperature target. When the probability of achieving the temperature target is raised to 66 percent, the remaining global budget is 590 $GtCO_2$eq [60]. Recent estimates assume an even smaller GHG budget of 530 $GtCO_2$eq (at a 50 percent probability of achieving the target) or 300 $GtCO_2$eq (at a 66 percent probability) [61].

The remaining GHG budget for Austria to achieve the +1.5 degree Celsius temperature target is between 280 $MtCO_2$eq (with a 66 percent probability and without incurring a higher temperature in the meantime) and 610 $MtCO_2$eq (with a 50 percent probability but a slightly higher temperature in the meantime) [60]. Based on calculations such as this, a climate protection target path for Austria can be derived, and it requires a reduction of approximately 4.5 $MtCO_2$eq per year until 2030 and of approximately 3.4 $MtCO_2$eq per year thereafter until 2040 [62].

When designing buildings that meet these specified climate targets, such distance-to-target weighting is one of the most common approaches [63]. The distance-to-target approach weights the environmental impacts based on the distance to a given target, e.g. the given climate target paths of the IPCC needed to reach the 1.5 degree Celsius target with a probability of 66 percent. Several distance-to-target approaches based on different targets have already been investigated [64, 65, 66, 67].

Although numerous studies have examined the derivations among the benchmarks of environmental indicators for buildings [68, 69], no harmonized benchmarks yet exist for building GHG emissions. Regarding the benchmarking of environmental impacts, a general distinction can be made between bottom-up and top-down approaches [70].

In the bottom-up approach, the environmental impacts are assessed from specific building inventories and scaled up by using data on the building stock and data on predicted future trends in the construction and renovation of buildings [71]. In contrast, the top-down approach starts from predefined policies and target values and attempts to infer the allowed environmental impacts of individual buildings [72].

Buildings are responsible for a significant portion of global GHG emissions, with annual building-related GHG emissions totalling 10 $GtCO_2$eq in 2021. In the annual status reports published by UN Environment, the IEA and the GABC, buildings and their operations account for 37 percent of the global energy and process-related emissions. Building operations account for approximately 28 percent of energy-related GHG emissions globally [33]. These energy-related GHG emissions are mainly generated by heating energy demand, cooling energy demand, ventilation energy demand, domestic hot water energy demand, and household electricity [73].

According to Austria's #mission2030, the level of GHG emissions from building operations must be reduced by 3 $MtCO_2$eq by 2030 (from the current level of approximately 8 $MtCO_2$eq to below 5 $MtCO_2$eq) [74].

However, due to the large share of embodied GHG emissions, from a holistic life cycle perspective, not only the use phase but also the construction and deconstruction phases, including all transport, of buildings are relevant factors in reducing the total GHG emissions generated by the building sector.

In this context, numerous studies in the literature have emphasized the importance of considering and reducing the embodied GHG emissions of buildings [75, 76, 77, 78, 79].

Thus, the main challenge for Austria from 2020 onwards is to ensure that buildings - both newly constructed and refurbished - meet the highest energetic standards. This means that buildings should operate under net-zero emission conditions so that they can produce heating, cooling, ventilation and hot water without relying on energy from fossil fuels [80].

2.2 Life cycle assessment of buildings

LCA has become a widely used tool for evaluating the environmental impacts of buildings over their entire life cycle. LCA provides a systematic framework for assessing the environmental performance of buildings, accounting for all stages of the building's life cycle, including material production, construction, use, and end-of-life [81].

LCA has been used to identify areas of improvement in a building's environmental performance, such as reductions in energy consumption, material use, and waste generation. The literature commonly recognizes that using LCA during the early planning phase of buildings carries significant potential for reducing their environmental impacts throughout their life cycles [82].

The LCA method is defined in the ÖNORM EN ISO 14040 and ÖNORM EN ISO 14044 standards [83, 84]. The methodology has been advanced in the construction sector by CEN/TC 350, particularly by standard EN 15978, which defines sustainability for the construction industry. In addition, standard EN 15978 specifies the assessment of the environmental performance of buildings using the LCA method [47].

During environmental building assessments, these standards have become established as the state-of-the-art. Accordingly, the LCA method includes four main steps: (1) goal and scope definition, (2) life cycle inventory analysis, (3) life cycle impact assessment, and (4) interpretation, as shown in Figure 2.2.

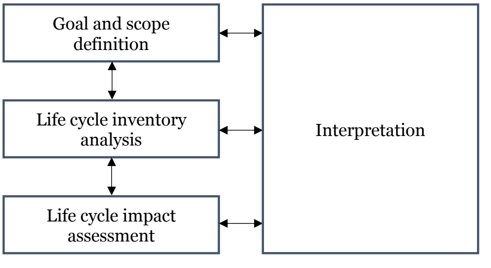


Figure 2.2: Framework of LCA [83]

The goal and scope of the assessment in the first step are defined, including the intended application, the system boundaries, the functional unit, and the reference flow [83, 84].

One of the most important steps in the implementation of an LCA is the definition of the functional unit. The functional unit is defined as a quantifiable description of the function of a product (or service) that serves as a reference for performing calculations and impact assessments. The function of a product (or service) can be based on various characteristics, such as technical quality, performance, and cost [83, 84, 85].

The life cycle inventory analysis that occurs in the second step involves the compilation and quantification of all inputs and outputs associated with the system under investigation, including energy and material flows, emissions to air, water, and soil and waste generation [83, 84].

The third step of the life cycle impact assessment involves evaluating the potential environmental impacts associated with inventory flows, which accounts for categories such as global warming, acidification, eutrophication, and human toxicity. Different impact assessment methods, including midpoint and endpoint methods, can be used to estimate environmental burdens [83, 84].

Finally, the interpretation performed in the fourth step provides insights into the results of the LCA study considering the assumptions, uncertainties, and limitations of the assessment. The interpretation may also involve the identification of opportunities for improvement and for communicating of the findings to stakeholders [83, 84].

2.3 Life cycle costing of buildings

LCC is a method used to evaluate the total costs of a product, process, or service throughout its life cycle. LCC involves defining the scope and boundaries of the analysis, collecting data throughout the product's life cycle, analysing the cost associated with the product or service, and interpreting the results to identify opportunities for improvement or cost savings [86].

Conducting LCC on buildings involves several steps that enable the total costs of a building over its entire life cycle to be recorded.

The first step is defining the scope and boundaries of the analysis. This is followed by identifying all relevant cost categories, including construction, operating, maintenance, and end-of-life costs. The next step is data collection. Then, the costs for each category are estimated and extrapolated across the entire life cycle of the building. Various factors are considered, such as the service life of the building components, inflation rate, interest rates, price increase rate, and maintenance cycles.

By considering all cost categories, LCC can help make informed decisions that account for both economic and environmental considerations.

LCC can be further categorized into three main types, namely, conventional life cycle costing (cLCC), environmental life cycle costing (eLCC), and societal life cycle costing (sLCC), as defined by Ciroth et al. [87].

In Figure 2.3, these three LCC categories are illustrated.

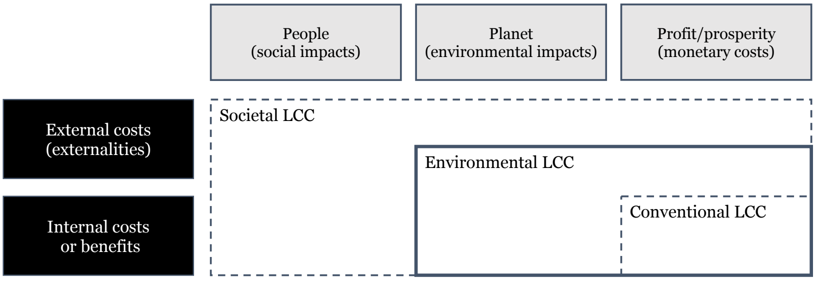


Figure 2.3: LCC categories [87]

Conventional life cycle costing

Notably, cLCC comprises the assessment of all costs incurred during the life cycle of a product and borne directly by the main stakeholders, i.e. the manufacturer, consumers or users. Since the costs are borne directly by the stakeholders involved, they are often referred to as internal costs. Thus, life cycle phases, such as the end-of-life phase, can be excluded from these calculations [87].

Principles and guidance for the calculation of the life cycle costs of buildings are defined in EN 16627 [88]. The general framework for assessing the economic performance of buildings is defined at the international level in ISO 15686-5 and at the European level in EN 15643-4 [89, 90]. The ISO 15686-5 standard does not use the term cLCC but defines it as LCC in a narrower sense.

Environmental life cycle costing

The term eLCC, which was first used in 2005 by Reich [91], was introduced and then gradually accepted after the publication of 'Environmental Life Cycle Costing' in 2008 by the Society of Environmental Toxicology and Chemistry (SETAC) [87].

In this context, the ISO 15686-5 standard also defines the term whole life costing (WLC), which is understood as a form of LCC in a broader sense. The standard separates LCC in the narrower sense, which comprises construction, operation, maintenance, and end-of-life costs, and WLC, i.e. LCC in the broader sense, which is extended to include externalities, nonconstruction costs and income.

Thus, eLCC includes the cLCC, i.e. construction, operation, maintenance, and end-of-life costs, and the externalities included in the WLC approach as interpreted in ISO 15686-5 without accounting for nonconstruction costs and incomes [89].

The structure of eLCC, i.e. its (i) goal and scope definition, (ii) data collection, (iii) impact assessment and (iv) interpretation, is identical to that of LCA. In addition to accounting for internal costs, external costs are also accounted for in eLCC [92].

Generally, eLCC is a methodology aimed at investigating environmental impacts in conventional LCC analysis. The methodology provides a comprehensive economic evaluation of a product or system, accounting for not only direct costs but also the external costs associated with environmental impacts. Thus, eLCC can help decision makers identify cost-effective options to reduce the environmental impact of buildings over their entire life cycles. eLCC was initially defined by Rebitzer as an LCA-based LCC method that utilizes an LCA model as a basis for estimating incurred costs in a product assessment [93].

Various studies have explored the development and application of eLCC in the building sector. For instance, Miah, Koh, and Stone proposed a framework for integrating the environmental and economic data in LCC and eLCC [94], while De Groot et al. developed an eLCC model for residential buildings [95].

In recent years, studies have focused on the application of eLCC in the building sector, such as the use of eLCC in wastewater treatment facilities, as discussed in the study of Rebitzer, Hunkeler, and Jolliet [96], and the use of eLCC in the early stage of precast concrete panel production for the energy renovation of existing buildings, as discussed in Zhang et al. [97].

Societal life cycle costing

The sLCC goes one step further than the eLCC and considers both environmental and social impacts, i.e. the effects on social well-being or job quality [92]. No sLCC was conducted in this doctoral thesis.

2.4 Economic instruments for building-related climate damage

As climate change becomes more severe, the interest in compensating those who have suffered losses due to damage caused by climate change is increasing. Economic compensation means giving money or offering other support to individuals, communities, or countries affected by climate change [98].

In the building sector, economic compensation can help pay for the damage caused by extreme weather events such, as floods and hurricanes, or for upgrading buildings to make them more energy efficient [99].

In the field of climate change mitigation, three main concepts are used to describe economic compensation for building-related climate damage.

The concept of opportunity costs refers to the costs associated with not pursuing an alternative course of action that would have led to a better outcome. In this context, opportunity costs refer to the benefits that could have been gained by investing in low-carbon alternatives rather than by relying on high-carbon activities that contribute to GHG emissions reduction [100].

The concept of abatement costs, on the other hand, refers to the costs of reducing GHG emissions through various mitigation measures, such as switching to renewable energy sources, improving energy efficiency, or implementing carbon capture and storage technologies. These costs may include both the direct costs of implementing the measures (such as equipment and labour costs) and the indirect costs incurred through lost economic opportunities or productivity resulting from the implementation [101].

The third concept is the evaluation of external costs. External costs are those associated with a product or service that are not reflected in the market price of that product or service and are therefore borne by society as a whole rather than by the producer or consumer of the product or service. In the context of the building sector, external costs can include the cost of the environmental and social damage caused by the consumption of energy and materials, the emission of pollutants and GHGs, and the disposal of waste. These external costs account for a significant part of the total economic costs of the building sector [102].

In the building sector, approaches to assess external costs have been included in ISO 15686-5 for years. According to ISO 15686-5, external costs are defined as *'quantifiable costs or benefits that occur when the actions of organizations and individuals have an effect on people other than themselves.'* Additionally, they are defined as *'costs associated with an asset that are not necessarily reflected in the transaction costs between provider and consumer and that, collectively, are referred to as externalities'* [89].

In the context of economic compensation for climate damage, carbon pricing instruments[1] are becoming increasingly popular in the construction industry as a way to tackle increasing GHG emissions. These instruments involve placing a cost on GHG emissions, which is typically enabled through a tax or cap-and-trade system and provides companies with an economic incentive for reducing their emissions [103, 104, 105]. The two main types of carbon pricing instruments are external and internal. In Figure 2.4, an overview of various carbon pricing instruments is presented.

[1] In this doctoral thesis, the term carbon price includes concepts such as CO_2 price, shadow price and results-based climate finance carbon price but always describes the price for one ton of CO_2eq.

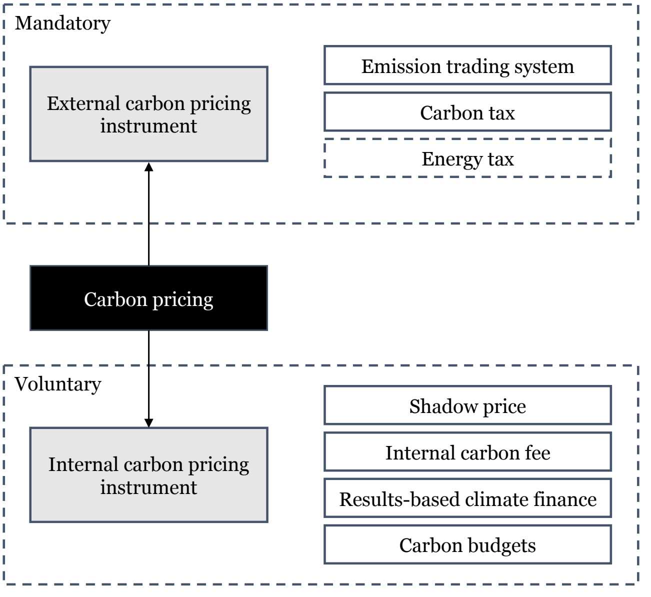


Figure 2.4: Types of carbon pricing instruments

External carbon pricing instruments

External carbon pricing instruments, such as carbon taxes and emissions trading systems (ETSs), are implemented by governments and apply to a wide range of emitters. These instruments create an economic incentive for emitters to reduce their emissions by increasing their costs of emission [106, 107].

Carbon tax

Carbon taxes are increasingly being used as a way for governments to tackle climate change by reducing the level of their countries' GHG emissions. Over 40 countries worldwide have implemented some form of carbon pricing, with carbon taxes being the most popular mechanism for promoting this goal. Different countries have designed their carbon taxes in different ways, with some targeting specific sectors or activities while others being more broadly applied to all carbon emissions [108].

The carbon tax is based on Pigouvian tax theory. The Pigouvian tax aims to correct undesirable market developments from any market activities that cause negative externalities by internalizing them. This means that external costs, which are generated by the producer but are not included in the market price, are covered by this tax [109]. Therefore, the carbon tax can also be classified as a price-based taxation system. A frequently mentioned example in this context is the environmental pollution and increased health care costs that result from the tobacco industry [110].

As part of the eco-social tax reform in Austria, a carbon price for carbon dioxide emissions was levied beginning in October 2022. This carbon tax amounts to 30 € per ton of CO_2eq and is intended to make reliance on fossil fuels more expensive than at present. Among other things, this tax affects gasoline prices, diesel prices and the price of oil used for heating. The effect of such carbon pricing is that companies that import fuel to Austria or produce fuel domestically are no longer required to pay only the mineral oil tax. Rather, they now have to pay an additional 30 euros per ton of CO_2eq (carbon dioxide) produced by burning their fuels [111].

Emissions trading systems

The second economic compensation model for achieving climate protection targets is certificate trading. ETSs are an instrument of climate policy that aim to reduce GHG emissions at the lowest possible economic costs by issuing a limited number of emission rights and subsequently trading them on a market. While the carbon tax is a price-based taxation system, certificate trading is quantity-based [112].

Governments worldwide are increasingly turning to ETSs as a way of reducing GHG emissions. An ETS works by setting a cap on the total amount of emissions allowed in a particular sector or region and then issuing permits that companies can buy or sell, thus allowing them to emit a certain amount of GHG emissions. Over time, the number of permits issued is reduced, creating a financial incentive for companies to reduce their emissions [103]. Currently, more than 35 countries and regions have implemented some form of ETSs, including the EU, China, and California [113].

There are two main forms of ETSs: (i) cap-and-trade and (ii) baseline-and-credits. The cap-and-trade system *'sets an absolute limit or 'cap' on the total amount of certain greenhouse gases that can be emitted each year by the entities covered by the system. This cap is reduced over time so that total emissions fall.'* [112].

The EU ETS is based on the cap-and-trade system. In this system, entities are forced to buy allowances if they exceed the cap. The baseline-and-credits system sets a standard level or 'baseline' for GHG emissions that are permitted to be emitted by the entities. If the entities stay under this baseline, they generate credits that they can sell to other entities [114].

Internal carbon pricing instruments

Other options aside from external carbon pricing instruments include various types of internal carbon pricing instruments.

Internal carbon pricing instruments are used by companies and organizations to account for the costs of their emissions when engaging in decision making processes. By doing so, companies can account for the environmental and financial costs associated with their emissions, and a financial incentive is created for reducing their carbon footprint. The specific method for implementing internal carbon pricing varies depending on the company but typically involves setting a price for each ton of CO_2eq produced. This price can be used to evaluate the financial impact of projects, investments, or operations that emit GHGs. The idea behind internal carbon pricing is to encourage companies to reduce their emissions and invest in low-carbon technologies through the creation of a cost incentive. An increasing number of companies are adopting this approach, and some are even incorporating it into their financial reporting [115].

Different methods can be used to set the price, such as using an external carbon market price, modelling different carbon price scenarios or setting a price based on the company's objectives. Regardless of the specific approach taken, internal carbon pricing is an effective way for companies to take responsibility for their emissions and to work towards reducing their carbon footprint [115].

These internal instruments can include shadow prices, internal carbon fees, results-based climate finance (RBCF) approaches and carbon budgets [104, 116, 117]. Numerous studies exist on the definition of carbon prices [102, 118, 119, 120, 121].

Carbon pricing using shadow prices

Shadow pricing is a method that organizations use to estimate the financial value of externalities, such as the environmental impacts of their actions. Doing so allows them to account for the social and environmental costs of their operations and creates incentives for reducing negative impacts [122]. The process of shadow pricing involves assigning a hypothetical price to the externalities associated with a company's activities; this price is calculated based on market data, scientific models or stakeholder engagement and can then be included in financial evaluations, such as project cost–benefit analyses, to better inform decision making. Shadow pricing can be used to address a range of environmental impacts, such as carbon emissions, water use and waste generation [123].

Although there is no standard methodology for shadow pricing, its adaptability and flexibility make it a useful tool for businesses and policy makers seeking to address the social and environmental impacts of their actions.

Carbon pricing using results-based climate finance

RBCF is a type of climate finance in which funds are paid out by climate finance providers through a climate fund to the recipients when predefined climate-related outcomes are achieved. These outcomes are generally specified at the output level, meaning that RBCF can foster low-emission technologies or underlying climate deliverables, such as reductions in GHG emissions levels [124]. Consequently, the benefits of applying RBCF to GHG emissions reductions are provided ex post according to ex ante negotiated outcomes. These environmentally based targets are commonly quantified in tons of emissions, e.g. tCO_2eq, reduced from the atmosphere and are verified in many cases by third party experts [125].

Carbon pricing for the building sector

Carbon pricing instruments are also recognized in several studies as effective ways to incentivize emission reductions in the building sector. Gorbach, Kost, and Pickett provide a comprehensive review of carbon pricing mechanisms, highlighting the opportunities and challenges of different approaches. They discuss various types of carbon pricing mechanisms, including carbon taxes, cap-and-trade systems, and performance-based incentives. These authors also examine the role of policy in driving low-carbon building development through mechanisms such as mandatory building codes, financial incentives, and public–private partnerships [126].

Other studies review the role played by carbon pricing in promoting low-carbon building development, which provides an overview of current practices and future potential. These studies emphasize the need for long-term policy stability and coordination in promoting the adoption of low-carbon building practices and the importance of integrating carbon pricing mechanisms with other policy measures, such as building codes, labelling schemes, and energy efficiency standards [105].

Further studies on the application of carbon pricing instruments in the construction industry include Wang et al., Bergh and Savin and Blumberg and Sibilla [127, 128, 129]. These studies explore the impact of carbon pricing on building performance, energy consumption and the economy and the potential for carbon pricing to incentivize the adoption of low-carbon building practices such as energy-efficient technologies, renewable energy systems and green building certification schemes. Policy coordination, public–private partnerships and stakeholder engagement are emphasized as crucial to promoting the adoption of low-carbon building practices [127, 128, 129].

In summary, it can be concluded from existing studies that there is no scientific consensus on the level at which a carbon price can be set to mitigate climate damage from the building sector.

2.5 Life cycle assessment and (environmental) life cycle costing in building procurement processes

In Austria, the procurement process regarding buildings for public- and sector-awarding authorities is subject to the federal public procurement act. The federal procurement act provides a comprehensive set of rules for the implementation of the tendering and awarding process for construction, service and supply contracts. Through constant amendments concerning sustainable procurement, the act also furthers the development of European directives. In 2004, the EU presented environmental and social concerns in a public procurement directive and defined them as so-called secondary considerations [130]. On the condition that bidders meet certain minimum requirements, EU directives 2004/17/EC and 2004/18/EC specified the awarding of contracts on the basis of price. A second option, which enables awarding contracts on the basis of the MEAT, was also added [36, 37].

One of the objectives of these developments in the procurement process for buildings and of the EU directives is the reduction in the energy consumption and GHG emissions of buildings. This is also why certain conditions for achieving these objectives must be placed into the tendering and awarding process for building construction [131].

Legal prerequisites already exist for the application of LCA in the awarding procedure. According to section § 20 (5) of the federal procurement act of 2018, the '*environmental compatibility of the service must be accounted for*'. This includes, in particular, the core elements of the LCA, namely, '*energy efficiency, material efficiency, waste and emission prevention* and *soil protection*'[132].

However, the scope, weighting and methodology of this consideration have not been specified by legislators. The quality labels and environmental management regulations put in place by public procurement law (cf. section § 87 and section § 108 federal procurement act 2018) appear too abstract to ensure that the environmentally best construction project is selected in each case. Energy efficiency is provided as a criterion for the award of supply and service contracts only by public-awarding authorities in the upper threshold range (cf. § 95 federal procurement act 2018) [132].

Therefore, the practice of tendering and awarding requires specific methodological tools for evaluating and assessing the development of eco-efficiency award criteria. To be applied in a legal manner, these awards must comply with the transparency obligations set out under EU law (ECJ 10.5.2012, Rs C-368/10, Max Havelaar) [133].

In this context, studies have already investigated the integration of LCA into the procurement process. In 2004, a guideline for the application of the LCA for environmental procurement was developed by Schenck [134]. The guideline was tested using a case study, and the findings showed that the LCA can be used for award decisions [134].

Several approaches to integrate the LCA into the acquisition process were also developed by Hochschorner and Finnveden [135]. In the application of LCA, four areas were identified: (i) increasing the level of know-how regarding the environmental requirements of products, (ii) fulfilling customer requirements, (iii) setting environmental requirements, and (iv) deciding between alternatives [135].

Similarly, in the work of Du et al., for support in the procurement decision, LCA was applied in the procurement process for bridges. Their study showed that indicators and calculation principles and weighting must already be comprehensively and transparently defined in the procurement process [136].

The possibility of LCA application in the public procurement process has also been shown by Vidal and Sánchez-Pantoja [137], who analysed LCA to evaluate the environmental performance during the procurement of furniture. The study showed that LCA can be implemented during the awarding procedure and can also be accounted for as an award criterion. However, the study found that the application of LCA in the furniture procurement process has significantly less scope and complexity when defining a clear functional unit compared to the application of LCA in the procurement process for a whole building [137].

Additionally, applying LCC to the tendering and awarding process for buildings has become increasingly important in recent years. However, LCC implementation in the procurement process still faces several barriers.

The methodological challenges include a lack of comparability between LCC tools and data, the complexity of LCC calculations, and the lack of robust data and information on the bidding process [138, 139, 140, 141, 142].

The organizational barriers relate to a lack of access to high-quality, reliable data and the absence of LCC competencies among users, resulting in insufficient support and training being provided by leadership [143, 144, 145].

The inclusion of LCC in the bidding process is clearly slowed by the barrier of the identified additional costs to the bidder for applying LCC to the bidding process [146, 147]. Awarding authorities are not willing to provide compensation for conducting LCC practices or for the extra effort of the bidder. In addition to the extra costs incurred by the bidder, higher acquisition costs and bidder prices have been identified as barriers positioned by the awarding authority [141, 148]. The inclusion of LCC in the bidding process imposes additional costs on bidders, resulting in higher acquisition costs and tight budgets. Cost considerations and the lack of a mandate for LCC usage in tendering processes are the most significant barriers [143, 149].

Barriers on the policy level include the lack of legally mandated environmental requirements and standardized processes, resulting in a lack of guidelines and incentives for LCC in the procurement process. Moreover, the lack of subsidies, incentives, and understanding regarding LCC hinders its implementation [150, 151].

2.6 Building certification systems and systems thinking-based planning processes

Building certification systems

In addition to LCA and LCC, numerous other sustainability assessment frameworks, such as building certification systems, have been developed at the building level during the last thirty years [22, 23, 24].

Therefore, building certification systems currently play a crucial role in promoting sustainable and environmentally friendly building practices. The areas covered by these systems are diverse, ranging from a single area, such as energy efficiency, to a wide range of areas across all three dimensions of sustainability, i.e. environmental, economic, and social [152].

The World Green Building Council (WGBC) provides a list of all building certification systems currently registered with the WGBC [153].

The building certification systems in Austria include the certification system of the Austrian Sustainable Building Council (German: Österreichische Gesellschaft für Nachhaltige Immobilienwirtschaft) (ÖGNI), the klimaaktiv certification system, and the total quality building (TQB) certificate. The ÖGNI building certification system is based on the German DGNB system, places particular emphasis on holistic sustainability and includes criteria for six different qualities, i.e. environmental quality, economic quality, sociocultural and functional quality, technical quality, process quality and site quality [154]. The klimaaktiv criteria catalogue is used to document and evaluate the energy and environmental quality of newly constructed and renovated buildings. The evaluation and quality assurance of buildings using the klimaaktiv criteria is based on a 1,000 point system [155]. In contrast, the TQB certificate was founded by the Austrian Sustainable Building Council (German: Österreichische Gesellschaft für Nachhaltiges Bauen) (ÖGNB) and is focused on five different categories, i.e. location and facilities, economy and technical quality, energy and supply, health and comfort and resource efficiency [156].

One of the objectives of building certification systems is to set minimum requirements for their target achievement across many criteria in the form of quantifiable benchmarks. In this context, studies have also analysed reference values for LCA and LCC in different building certification systems [157, 158].

Furthermore, some studies have compared and contrasted building certification systems in general [152, 159, 160]. One of the most recent studies on this topic analysed ten different building certification systems and compared their criteria from the perspective of the three dimensions of sustainability. The study showed that the structure of building certification systems and the weighting of the criteria vary greatly, making it difficult to directly compare assessments based on different building certification systems [161].

Systems thinking-based planning processes

In the past, the focus of building planning optimization was primarily on reducing the final energy demand in the operational phase of buildings, e.g. through increased insulation. Decisions concerning planning measures were therefore reduced to a criterion that was directly evaluated (i.e. energy performance) within the sustainability assessment of buildings. This linear assessment approach is characterized by applying only a single criterion in the assessment of planning measures without considering their environmental and/or economic impact [162]. Therefore, the interdependencies of other criteria and their influence on the overall performance of a building are often neglected, especially in the early planning phases [163, 164, 165, 166].

In contrast, systemic thinking has received increasing interest in recent years [87, 167, 168]. Different systemic approaches related to criteria interdependencies were described in [169, 170, 171]. The use of a systemic approach in multicriteria evaluations enables the modelling of the previously mentioned criteria interdependencies and the identification of system synergies and trade-offs [172, 173].

For this reason, different methods, such as system dynamics, systems thinking and systems engineering, have been established in recent years to help manage this increased complexity.

The methodological system dynamics approach was initially developed by Forrester in 1971. The primary objective of evaluating system dynamics is to acquire an understanding of complex system nonlinear behaviour over time. The extensive work by Forrester on system dynamics is available through the Massachusetts Institute of Technology (MIT) homepage [175].

In the field of engineering, system dynamics gave rise to the development of systems engineering. Systems engineering, similar to system dynamics, is rooted in systems thinking and relies on a variety of tools, such as requirements analyses, simulation, and modelling. These tools are increasingly being used during the building planning phase, as noted by Zavadskas et al. in 2021 [176].

Systems thinking has its origins in general systems theory developed by Von Bertalanffy [177] and is used to solve complex problems that cannot be solved with conventional reductionist thinking [178].

The term systems thinking was introduced in 1987 by Richmond, who defined systems thinking as follows: *'As interdependency increases, we must learn to learn in a new way. It's not good enough simply to get smarter and smarter about our particular 'piece of the rock.' We must have a common language and framework for sharing our specialized knowledge, expertise and experience with 'local experts' from other parts of the web. We need an Esperanto system. Only then will we be equipped to act responsibly. In short, interdependency demands systems thinking. Without it, the evolutionary trajectory that we've been following since we emerged from the primordial soup will become increasingly less viable'* [179, 180].

Senge and Sterman, other systems thinking pioneers, added that systems thinking is a method for seeing the whole and, thus, is a framework used for seeing interconnections rather than individual elements in a system [181, 182]. Detailed explanations of the systems thinking method can be found in the literature, which is reviewed in these studies by [178, 183, 184, 185].

In recent years, the building sector has been incorporating systems thinking-related approaches to improve building design, construction, operation and maintenance. These approaches recognize the interdependencies among various aspects of building systems. One of the approaches used is integrated project delivery, which involves collaboration among different stakeholders, including architects, engineers, contractors, and building owners, from the initial planning phase to construction and beyond. Integrated project delivery promotes the early involvement of stakeholders, open communication and the sharing of risk and rewards [186, 187].

Another approach is that of design thinking, which emphasizes a user-centred and iterative approach to design that involves multiple stakeholders, including building occupants, in the planning process. Design thinking fosters empathy regarding users and their needs, generates innovative and creative solutions and promotes collaboration and iteration [188, 189]. In addition, Zavadskas et al. highlighted the significance of building management tools for stakeholders that are constructed for sustainability criteria in the building planning phase in general [176].

Neumann went into detail by emphasizing the fact that the main reason for not analysing cause–effect relationships through the use of tools and methods is because these tools and methods are too sophisticated [190]. With the development of the know-why method, Neumann provideed a qualitative model method that, unlike quantitative model methods, does not require specific data, equations or parameters. The legitimacy of this method is underscored by the fact that reliable data are lacking for many problems and challenges, which makes an analysis based on abductive-logical inferences, i.e. an observation of the effects of a hypothesis that is deemed valid as long as it can be disproved, sufficient. The theoretical basis of the know-why method and numerous model examples can be found in [190].

In this context, initial approaches based on the know-why method were developed by our Working Group Sustainable Construction at Graz University of Technology [172, 173]. In these studies, we identified the interactions of sustainability aspects based on the criteria of the DGNB building certification system and modelled the interactions using the know-why method. Moreover, the application for the implementation of a systemic planning process of sustainable facades shows that stakeholder preferences can be met more efficiently by using the know-why method [191, 192].

2.7 Identified research gaps

In summary, the following research gaps can be identified in relation to the implementation of an LCA-based building procurement process and its integration into the tendering and awarding phase in practice:

- Although EU Directive 2014/24/EU [38] emphasizes procurement based on LCC and the monetary consideration of environmental externalities, there is no cost model for Austria that takes into account environmental impacts during building procurement.

- Therefore, no standardized guidelines exist for bidders or awarding authorities in Austria in the implementation of LCA in the building procurement process, as there are, for example, for LCC in the awarding process [193, 194].

- One of the main reasons LCA is not implemented in the building procurement process is due to methodological obstacles caused by the method itself. These include, for example, missing data, nonharmonized databases and software tools, insufficient data quality and data uncertainties.

- Apart from the ETSs [195] and the introduction of a CO_2 price [196], no additional economic compensation for climate damage caused by the building sector (e.g. by monetizing GHG emissions) is currently envisaged in Austria.

- In this context, there is still no scientific consensus on the level of carbon prices. This concerns both the level of CO_2 prices relative to CO_2 taxes and the level of other carbon pricing instruments such as the shadow price.

- Because of this lack of consensus on carbon pricing levels, and because of the unique nature of buildings, there is no defined threshold for carbon pricing in the building sector to drive more environmentally friendly procurement decisions.

- Although the requirements for buildings and thus also for the building procurement process are constantly increasing, the application of systemic planning approaches is not state-of-the-art. One of the approaches that would be useful in this regard is the know-why method [197], which is currently not used in the planning phase of buildings.

3 Methods

In this section, the main methods applied in this doctoral thesis are presented.

Figure 3.1 displays an overview of the methods and matches the thesis publications to them.

	Systematic literature review	Case study approach	Life cycle assessment	Environmental life cycle costing	DGNB building certification system	Know-why modelling
Thesis publication 1	x		x			
Thesis publication 2		Modelled instrumental case study	x	x	x	
Thesis publication 3		Collective case study	x	x		
Thesis publication 4		Collective case study	x	x		
Thesis publication 5		Case study combination			x	x

Figure 3.1: Methods applied in the five thesis publications. In the research different case study approaches were used: (i) modelled instrumental case study, (ii) collective case study and (iii) modelled collective case study. In some thesis publications only the principles of the mentioned methods were applied (see dashed frames).

In thesis publication 1, the SLR method was applied to analyse the application of LCA in the procurement process for buildings and to identify the key barriers and challenges that hinder the successful implementation of LCA in the tendering and awarding process. The LCA method provided the focus of the investigations in terms of content, but no LCA calculations were conducted.

In thesis publication 2, the LCA and LCC principles were applied to the tendering and awarding process for buildings using a modelled instrumental case study. Furthermore, the principles of internal carbon pricing instruments were used to internalize GHG emissions and calculate the GHG emissions bonus/malus. For the definition of an environmental exclusion criterion the limit value was taken from the LCA criteria of the DGNB building certification system.

In thesis publication 3, the LCA method was applied to evaluate the environmental impacts and the LCC method was applied to evaluate the economic impacts of 37 scenarios of a two-story residential building (collective case study).

In thesis publication 4, the LCA and LCC inventories of thesis publication 3 were used to analyse the impact on the award decision based on different award models, i.e. awarding contracts based on the lowest prices, awarding contracts based on LCC, awarding contracts based on eLCC and awarding contracts based on the Paris-compatible cost (PCC) scenarios using the developed LCA-based bonus/malus system. For the calculation of external costs, internal carbon pricing instruments were used to identify environmental break-even points for the level of carbon prices.

In thesis publication 5, the hierarchical reference-based know-why model was developed to examine the interactions of different sustainability criteria and, thus, ensure the systemic and holistic planning of buildings. In this context, the concept of the know-why method was applied and combined with the principles of hierarchical decision making (HDM). The sustainability criteria were based on the DGNB building certification system.

3.1 Systematic literature review

The SLR method is used to obtain a comprehensive overview of a research area and subsequently identify research gaps for future investigations. Therefore, the SLR of publications is used throughout this doctoral thesis to position the work within the existing body of literature.

The SLR steps are described in detail in the preferred reporting items for systematic reviews and meta-analyses (PRISMA) guidelines and the Cochrane handbook for systematic reviews. While the SLR and data analysis were conducted, the 27-item checklist of the PRISMA guideline was followed to ensure a transparent, complete, and accurate review [198, 199].

The main steps of the SLR were the (i) definition of research question(s), (ii) definition of keywords and search strings, (iii) definition of constraints, (iv) article exclusion by title, (v) article exclusion by abstract, (vi) article exclusion by full paper and (vii) meta-data analysis.

In addition to the PRISMA guideline, the snowball approach described by Wohlin was applied in iterative steps [200].

In SLR, the keywords procurement, tender, bid, award, LCA, EPDs, product environmental footprint and carbon footprint were all used. The search was limited to the years 2000-2020, articles published in the English language, and review or research type articles. After applying these constraints, 569 articles were selected from the ScienceDirect and Scopus databases.

After the exclusion processes and the application of the snowball approach, 19 articles were included in the final meta-data analysis.

3.2 Case study approach

Case studies are used to gain a more extensive and detailed understanding of a complex subject area in its real-world setting [201].

The case study research design has been established in many disciplines and is mainly applied in the social sciences [202]. However, especially in the construction industry, the case study approach is a frequently used research design due to the uniqueness of buildings and the complexity of their preceding systemic planning process [203].

Stake distinguished the three case study types as follows: (i) intrinsic case study, (ii) instrumental case study and (iii) collective case study [204]. Throughout this doctoral thesis, different types of case studies were used.

Modelled instrumental case study for the development of the LCA-based bonus/malus system

For the first application (pilot case) of the newly developed LCA-based bonus/-malus system, which is designed to be applied in the tendering and awarding process for buildings an instrumental case study was modelled. Due to the binding laws and standards of the tendering and awarding process, which make practical applications difficult, this particular case study approach was chosen. The modelled case study was based on the fundamentals of the case study approach as set out by Crowe et al. and included the phases of (i) defining the case(s), (ii) selecting the case(s), (iii) collecting and analysing the data, (iv) interpreting the data, and (v) reporting the results [202].

The modelled case study was based on 7 hypothetical bids for an office or educational building of a net floor area (NFA) of 5.000 m^2. The set GWP values were based on the GWP benchmark range between the target value (13.33 $kgCO_2eq/m^2_{NFA}a$) and the reference value (27.72 $kgCO_2eq/m^2_{NFA}a$) of the DGNB building certification system for the building schemes office and educational buildings [31]. Values between approximately 1.800 and 2.200 $€/m^2_{NFA}$ for standard office and educational buildings based on the building cost index (German: Baukostenindex) (BKI) were assumed to estimate the bid prices and multiplied by the defined NFA [205]. In addition, the shadow price and the RBCF carbon price, were set according to values from the literature and used to monetize the environmental impacts [119].

Table 3.1 shows the defined assumptions, which were used to model the instrumental case study.

Table 3.1: Assumptions in the modelled instrumental case study for the first application (pilot case) of the LCA-based bonus/malus system.

Values between 1.800 and 2.200 based on BKI (Price) | Defined NFA for an office or educational building (NFA) | BKI values multiplied by the NFA (Bid price)

Price in €/m²	GWP in $kgCO_2eq/m^2_{NFA}$ a	NFA in m²	RSP in a	Bid price in €		GWP in tCO_2eq	
2.074	23	5.000	50	Bid price 1	10.370.041	Bid 1	5.750
1.804	24	5.000	50	Bid price 2	9.020.200	Bid 2	6.000
1.886	26	5.000	50	Bid price 3	9.433.478	Bid 3	6.500
2.164	18	5.000	50	Bid price 4	10.821.849	Bid 4	4.500
2.013	22	5.000	50	Bid price 5	10.068.947	Bid 5	5.500
1.886	15	5.000	50	Bid price 6	9.433.273	Bid 6	3.750
2.162	20	5.000	50	Bid price 7	10.811.394	Bid 7	5.000

GWP (kgCO₂eq): Values between the target value (13,33) and the reference value (27,72) of the building schemes office and educational buildings of the DGNB building certification system

RSP: Reference study period for a building life cycle according to EN 15978

GWP (tCO₂eq): GWP values multiplied by the NFA and the RSP

Collective case study for the validation of the LCA-based bonus/malus system

For further validation of the LCA-based bonus/malus system, the concept of a collective case study was applied. Based on a two-story residential building, 37 different scenarios were developed, and both LCA and LCC were performed. The 37 scenarios were divided into the (i) low-energy housing standards, (ii) passive housing standards, and (iii) plus-energy housing standards, and strategies for optimizing environmental and economic performance were investigated.

Different scenarios were created by varying the construction materials, thermal insulation and technical building equipment [206, 207, 208]. Using this approach, a total of 37 scenarios were defined, each meeting the requirements of the respective energetic standard. The defined building scenarios were analysed for a reference study period (RSP) of 50 years and calculated using the calculation method defined in the energy performance regulation in Austria, and their structures were dimensioned to achieve a uniform heat demand.

Figure 3.2 shows the ground floor, upper floor and section of the two-story residential building, which was used as a collective case study.

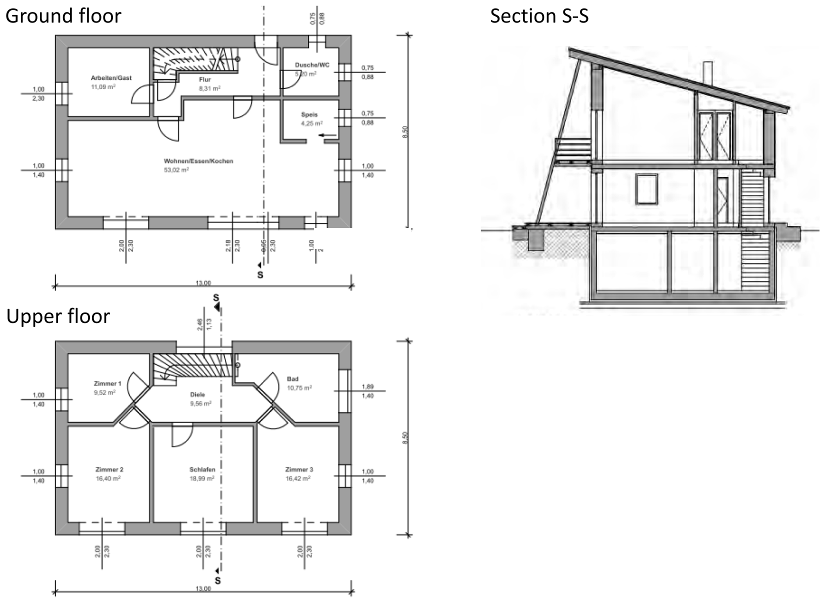


Figure 3.2: Collective case study for validation of the LCA-based bonus/malus system. Thirty-seven scenarios were created by varying the construction materials, thermal insulation and technical building equipment [206, 207, 208].

Combination of an instrumental case study and a modelled collective case study for the development and validation of the hierarchical reference-based know-why model

To examine the application of the developed hierarchical reference-based know-why model, an office building was used as an instrumental case study to define the reference alternative for the analysed building envelope.

Then, different types of building envelopes (according to the modelled collective case study approach) were planned for the office building, and their environmental, economic, sociocultural and functional, technical and process-related qualities were analysed.

Using the hierarchical reference-based know-why model made it possible to visualize the systemic interrelationships of these five qualities, identify the synergies and trade-offs among the qualities and thus safeguard against undesirable developments in the early planning phase.

Figure 3.3 shows the building envelopes (according to the modelled collective case study approach), which were analysed based on the reference office building (instrumental case study).

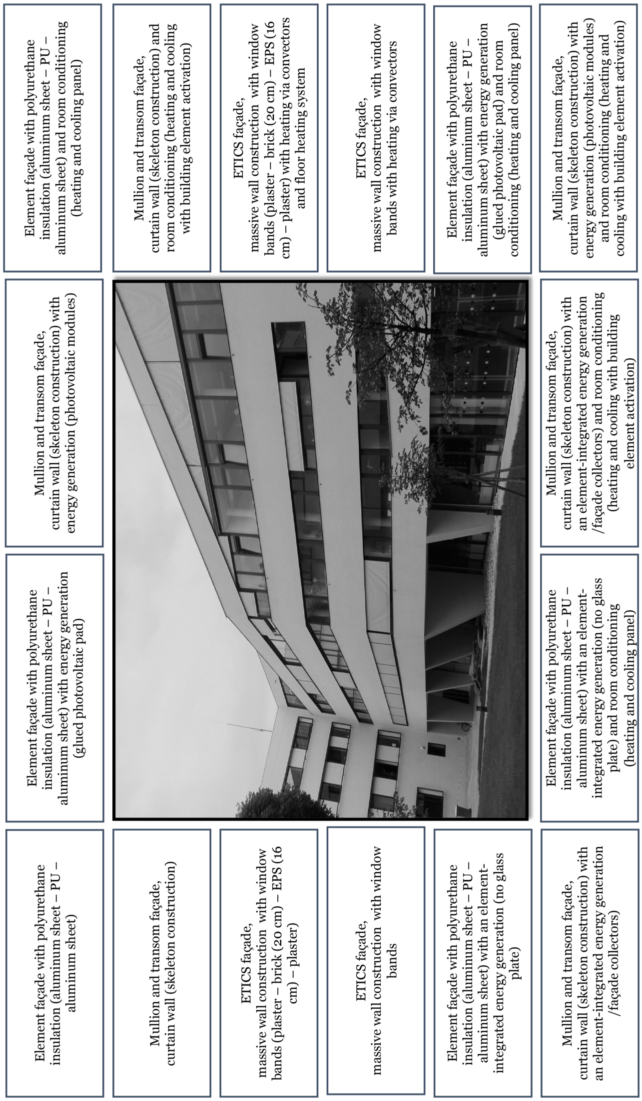


Figure 3.3: Building envelopes (modelled collective case study), analysed based on the reference office building (instrumental case study) for the development and validation of the hierarchical reference-based know-why model.

3.3 Life cycle assessment

Environmental impacts were assessed on the basis of the defined functional unit. The functional unit was set to 1 square metre NFA per year for the defined RSP of 50 years.

The impact potentials were calculated using the system model 'allocation, recycled content', which is also referred to as the 'cutoff approach', and the GWP indicator was calculated using the IPCC impact assessment method [209].

The system boundaries include the production stage modules (A1-A3), the construction process stage modules (A4-A5), the replacement module (B4), the operational energy consumption module (B6), and the end-of-life modules (C1-C4). The environmental impacts of the production stage modules (A1-A3) and end-of-life modules (C3, C4) were based on the material quantities described in the performance specifications. Module construction (A5) and module demolition (C1) impacts were included at 5 percent and 2 percent, respectively, of the product stage module (A1-A3) impacts [210].

In the inventory analysis[1], all structural elements, i.e. construction materials and insulation materials, and all of the technical building equipment used, were mapped in detail based on the performance specifications. The replacement of the building components and materials during its RSP were defined based on service life data for building components [211]. The impacts emitted in the operational stage of the building, i.e. heating, cooling, ventilation, hot water, lightening and appliances, were calculated for each of the scenarios based on the requirements set out in the Austrian energy certificates [212].

The 37 residential building scenarios were modelled using the LCA software SimaPro. In SimaPro, ecoinvent database v.3.6 was used to assess the environmental indicator GWP [213].

3.4 Environmental life cycle costing

The determination of life cycle costs is a prerequisite for calculating eLCC.

To determine the value of future cash flows and to ensure the comparability of costs over time, in this doctoral thesis, the net present value (NPV) method was applied to compare the economic performance in the scenarios of the two-story building [214, 215].

[1] A detailed LCA inventory can be found in the supplementary materials of thesis publication 3.

As in the LCA calculations the functional unit for the calculated life cycle costs was defined as € per square metre NFA per year for the defined RSP of 50 years[2].

Based on the performance specifications, the construction costs were calculated in accordance with ÖNORM B 1801–1 and ÖNORM B 1801–2 [216, 217]. To ensure comparability between the construction costs and embodied impacts, the costs of the replacement of building components as part of the maintenance costs were added to the construction costs.

The costs of the replacement of building components were based on their service life data [211]. The operational costs were based on the defined electricity price (0.17 €/kWh), the defined pellet price (0.25 €/kg) and the different heating demands of the different energetic standards [218, 219].

End-of-life costs were not considered because it is difficult to predict the technological development of dismantling and recycling methods over 50 years. Therefore, an estimate of end-of-life costs is subject to large uncertainties. Moreover, during discounting over the considered RSP, end-of-life costs become negligible compared to construction and operational costs [220]. Especially in variant comparisons, the delta between the deconstruction and recycling methods of different construction methods is very small.

Additional calculation parameters for the dynamic LCC (discount rate = 5.5 percent, inflation rate = 2.0 percent, escalation rate (energy) = 4.0 percent, and escalation rate (construction services) = 2.0 percent) were based on the DGNB building certification system [31].

As defined by Ciroth et al., the eLCC method is an extension of LCC to include selected external costs (see equation 3.1) [87].

$$\boxed{eLCC = LCC + External\ costs_n} \tag{3.1}$$

Carbon pricing using shadow prices

After the determination of the life cycle costs and the GHG emissions by conducting the LCA, shadow prices were used to determine external costs (see equation 3.2).

$$\boxed{External\ costs_n = GHG_{\text{emissions}_n} \times Shadow\ price} \tag{3.2}$$

To calculate the external costs, values from the scientific literature were used to define the shadow prices. The defined shadow price range and the RBCF carbon price range set for this study, i.e. 50 €/tCO_2eq to 400 €/tCO_2eq were

[2] A detailed LCC inventory can be found in the supplementary materials of thesis publication 3.

based on the Climate Change Center Austria (CCCA) experts' factsheet [119]. This initial value of 50 €/tCO_2eq was also in line with the EU average value of carbon prices [108].

Carbon pricing using results-based climate financing

The award scenarios after the application of the LCA-based bonus/malus system are called PCC scenarios. To calculate the PCC scenarios, equations 3.3 and 3.4 were used. Here, n represents the number of submitted bids.

$$\boxed{PCC_n = eLCC_n + GHG_{emissions_{bonus/malus_n}}} \tag{3.3}$$

where:

$$\boxed{GHG_{emissions_{bonus/malus_n}} = (GHG_{emissions_n} - \frac{\sum_1^n GHG_{emissions_n}}{n}) * RBCF\ carbon\ price} \tag{3.4}$$

Using the RBCF approach, the mean value of the GHG emissions of all valid submitted bids was determined. If the contract was awarded to a bidder whose GHG emissions were below this mean value, then monetizing this deviation with the RBCF carbon price resulted in a GHG emissions bonus. If the contract was awarded to a bidder with higher GHG emissions, then the monetization of the deviation from the mean value resulted in a GHG emissions malus.

The GHG emissions bonus/malus represents a type of RBCF. The amount of the GHG emissions bonus or malus was calculated in a similar fashion to external costs based on a shadow price range. Environmentally based targets were defined as a deviation from the classical RBCF. These were not defined in advance but rather were the result of the GHG emissions mean value of the individual projects submitted by all participating bidders. The RBCF approach shown in equation 3.4 is also illustrated in Figure 3.4.

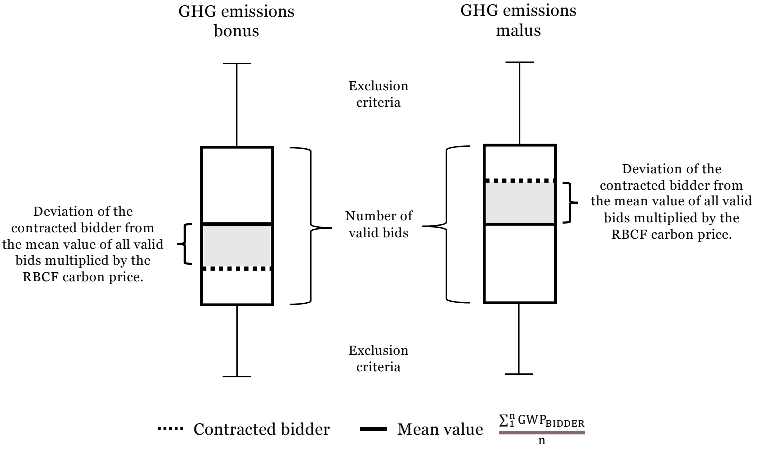


Figure 3.4: Schematic illustration of the results-based climate finance approach used within the LCA-based bonus/malus system.

3.5 DGNB building certification system

The DGNB building certification system is widely used for assessing the sustainability of buildings. It was developed by DGNB and is based on a comprehensive catalogue of criteria that cover various aspects of sustainability. Furthermore, the DGNB criteria catalogue is considered an advanced '2nd generation' building certification system and fulfils the requirements of the CEN/TC 350 standards [162].

The catalogue of criteria accounts for all relevant aspects of sustainability. This catalogue includes various categories, such as environmental quality, economic quality, sociocultural and functional quality, technical quality, process quality and site quality. Within each category, there are defined specific requirements and subcriteria that must be met to qualify for certification. In total, the building certification system comprises 37 sustainability criteria, which have different weights [31].

To achieve certain certification levels, the DGNB building certification system also provides GWP benchmarks. These benchmarks differ for different types of buildings and are further divided into benchmarks for embodied and operational GHG emissions.

For this reason, the benchmarks from this certification system were used to define the LCA threshold within the minimum criterion in the LCA-based bonus/malus system. Furthermore, the sustainability criteria built the basis for the systemic planning process in the hierarchical reference-based know-why model.

3.6 Know-why modelling

The know-why method is based on systems thinking principles. In this context, Neumann developed the know-why modelling approach to address the issue that most currently available tools are too complicated in their application to effectively use to analyse impact relationships [190].

The know-why method comprises the following four know-why questions, which can be answered qualitatively or semiquantitatively in an attempt to analyse and therefore understand complex systems [197]:

1. What leads directly to more of a factor right now?
2. What leads directly to less of a factor right now?
3. What might lead directly to more of a factor in the future?
4. What might directly hinder a factor in the future?

These four know-why questions are implemented in the software tool iMODELER [221], which was also used for the investigation in this doctoral thesis.

These questions can be applied to any factor, i.e. to any modelled element in the model. The iMODELER software tool can place any factor in the model at the centre of the model and thus allows these four questions to be asked and modelled for each element. This means that with the know-why method and the software tool iMODELER, not only can the criterion LCA-optimized planning be investigated, but also it is possible to consider more (or all) sustainability aspects of the DGNB certification system.

For the application in the hierarchical reference-based know-why model, the four know-why questions were modified as follows:

1. What directly leads to more of a factor right now compared to a reference alternative?
2. What leads directly to less of a factor right now compared to a reference alternative?
3. What might lead directly to more of a factor in the future compared to a reference alternative?
4. What might directly hinder a factor in the future compared to a reference alternative?

The definition of a reference alternative supports answering the four know-why questions, since each further planning alternative is evaluated on the basis of the neutral reference alternative. This means that for a factor under investigation, e.g. LCA optimization, a planning alternative can contribute more, the same amount or less than the reference alternative to the achievement of the factor's target. Figure 3.5 shows the principle of the know-why method in the iMODELER software tool.

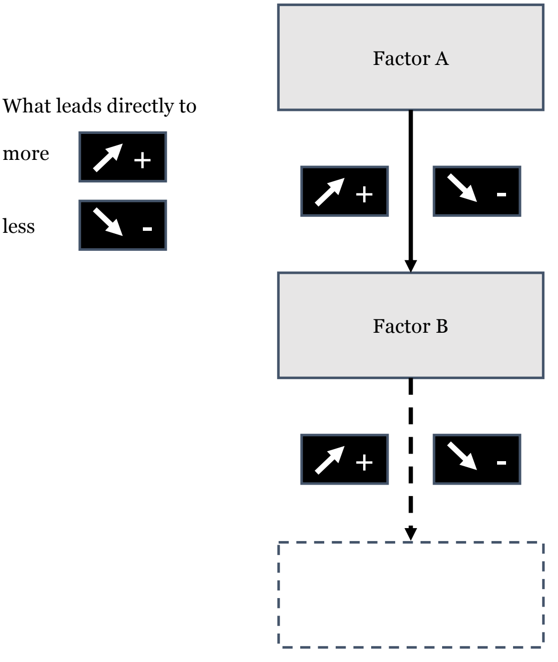


Figure 3.5: Know-why method in the iMODELER software tool [197].

4 Findings

This chapter presents the key findings of this doctoral thesis based on the five thesis publications [222, 223, 224, 225, 226]. The results are presented according to the defined subresearch questions.

4.1 Key barriers and challenges for the successful implementation of LCA in the tendering and awarding process for buildings

A state-of-the-art review was conducted in thesis publication 1 to analyse the implementation of LCA in the tendering and awarding process for buildings.

The SLR results showed that the LCA method is currently rarely used in the procurement process for buildings. Based on this finding, the articles from the final SLR sample were used to identify the key barriers to LCA implementation at this early project stage. The identified obstacles can be sorted into the following five categories: (i) methodological obstacles, (ii) organizational obstacles, (iii) governance obstacles[1], (iv) policy obstacles[2] and (v) economic obstacles.

Methodological implementation obstacles

There was a difference among these methodological implementation obstacles due to the LCA method itself and the implementation of LCA in the procurement process.

The most frequently cited key barrier was the complexity of conducting LCA. In this context, the fact that there are no guidelines or handbooks for LCA implementation in the procurement process for buildings has also been identified as a barrier. Furthermore, the quality of the data used in the preparation of inventories and their underlying uncertainties have also been identified as an implementation obstacle. Regarding the procurement process for buildings, it has been emphasized that environmental criteria are rarely demanded in tender documents and that there are no general guidelines on best practices for integrating environmental criteria into the procurement process.

[1]In thesis publication 1, this was initially defined as legal obstacles.

[2]In thesis publication 1, this was initially defined as political obstacles.

Finally, it has been claimed that environmental criteria are not weighted strongly enough and thus have no effect on the award decision. Additionally, the missed opportunity for monetizing the LCA results was identified as an implementation obstacle.

Figure 4.1 presents an overview of the methodological obstacles.

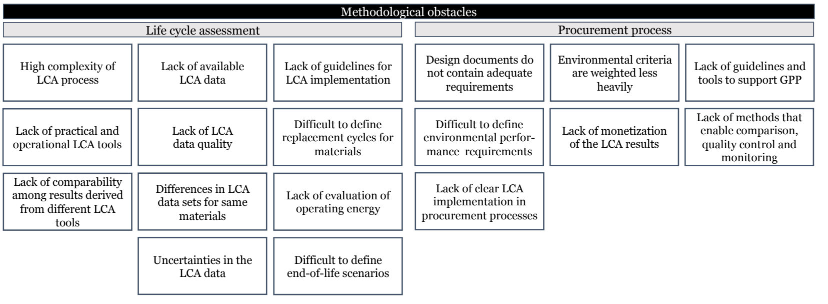


Figure 4.1: Methodological implementation obstacles to life cycle assessment applications in the procurement process for buildings.

Organizational implementation obstacles

In the organizational category, the implementation obstacles that affect stakeholders and organizations involved were considered. The obstacles to implementation can be divided into those that affect the awarding authority and those that affect the bidders.

The results show that the lack of know-how within organizations regarding LCA is an implementation obstacle.

The lack of resources with which to carry out the additional tasks and to cover the additional time required was also identified as an obstacle.

Another obstacle is the organization's level of access to data for conducting LCAs.

Regardless of the LCA results, organizations often do not have the means to offer more environmentally friendly alternatives or to compare them in the tendering and awarding process.

Regarding the procurement process in general, stakeholders appear to remain unaware of more environmentally friendly procurement processes and lack the know-how to formulate clear targets and mitigation strategies or the need to include these in the tender documents.

Another implementation obstacle is the lack of an actor, i.e. a sustainability assessment expert, who can supervise the LCA-based procurement process.

Figure 4.2 displays an overview of the organizational obstacles within the domains of the awarding authority and the bidders.

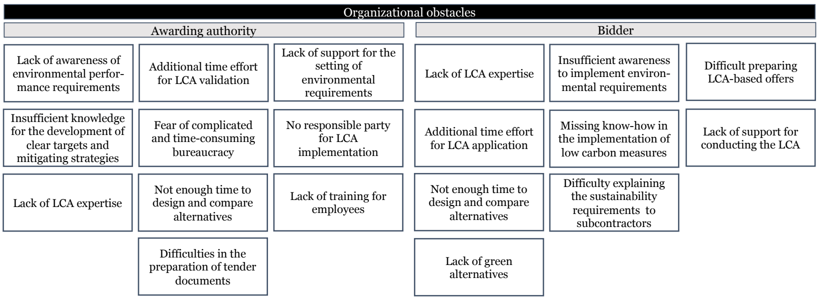


Figure 4.2: Organizational implementation obstacles to life cycle assessment applications in the procurement process for buildings.

Governance and policy implementation obstacles

On the governance level, one of the implementation obstacles is the lack of mandatory environmental requirements for LCA implementation. In this regard, it has also been mentioned that no established rules exist regarding how environmental criteria should generally be integrated into the procurement process and that no regulations exist for public tenders.

In the category of policy implementation obstacles, the lack of a comprehensive strategy for public procurement was identified. Regarding the implementation of LCA in the procurement process, no supporting initiatives exist at the policy level.

This also means that the relevant municipal authorities generally do not exercise the right to demand the implementation of sustainability aspects in general or the performance of an LCA in the tendering and awarding process for buildings.

Figure 4.3 lists the governance and policy obstacles.

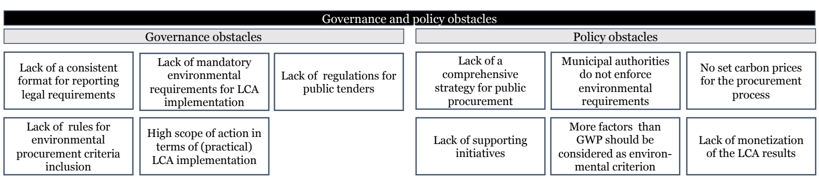


Figure 4.3: Governance and policy implementation obstacles to life cycle assessment applications in the procurement process for buildings.

Economic implementation obstacles

The economic implementation obstacles can be divided between the domains of the awarding authority and the bidders. Figure 4.4 illustrates the economic obstacles faced by the awarding authority and the bidders.

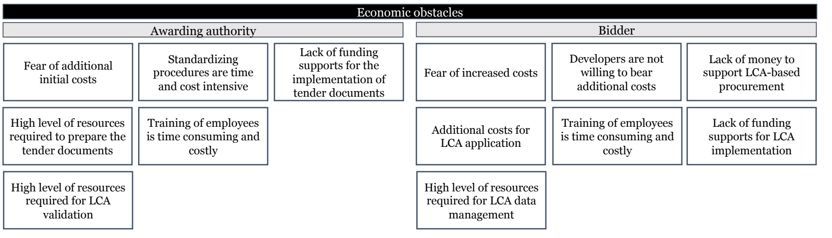


Figure 4.4: Economic implementation obstacles to life cycle assessment applications in the procurement process for buildings.

From an economic perspective, one of the implementation obstacles to LCA applications in the procurement process is the increased cost factor, i.e. the additional time and costs needed to prepare an LCA.

Furthermore, the additional costs, which are necessary for training staff, have been identified as an obstacle. In this context, no funding support is available.

The establishment of a standardized process for the future implementation of LCA in the tendering and awarding process for buildings has also been identified as being cost-intensive and, therefore, an implementation obstacle.

In general, the lack of funding for the implementation of an LCA-based procurement process is also an obstacle.

In summary, above all, there is a lack of the necessary know-how for conducting an LCA. This applies to both the awarding authorities and the bidders. This fact is underscored by the lack of guidelines to support both awarding authorities and bidders in conducting an LCA and to identify specific applicable measures. In conclusion, a financing funding system is also needed to meet the increased requirements for following an LCA-based tendering and awarding process.

4.2 Specific procedural steps to effectively implement monetized environmental indicators in the tendering and awarding process for buildings

Based on the current state of LCA application in the building procurement process and the identified implementation obstacles, thesis publication 2 developed a framework that includes individual process steps to implement LCA and monetize GHG emissions in the tendering and awarding process for buildings.

Theoretical framework

The prerequisites for applying the developed framework in practice are as follows:

1. adapting the tender documents,
2. conducting an LCA when preparing the offers,
3. monetizing GHG emissions using carbon pricing instruments,
4. internalizing the external costs in the bid price,
5. considering the GHG emissions bonus/malus,
6. awarding contracts according to the lowest PCC scenarios, and
7. establishing a climate fund to finance the GHG emissions bonus and to handle the payment flows for external costs and the GHG emissions malus.

As shown by the applied equations, early sustainability assessments, i.e. environmental performance determined through LCA and economic performance determined through LCC, are necessary for the implementation of the LCA-based bonus/malus system.

Therefore, in the first step, the awarding authority must define all of the required information for the application of the LCA-based bonus/malus system in the tender documents.

Figure 4.5 shows the adapted procurement process for the LCA-based bonus/-malus system implementation.

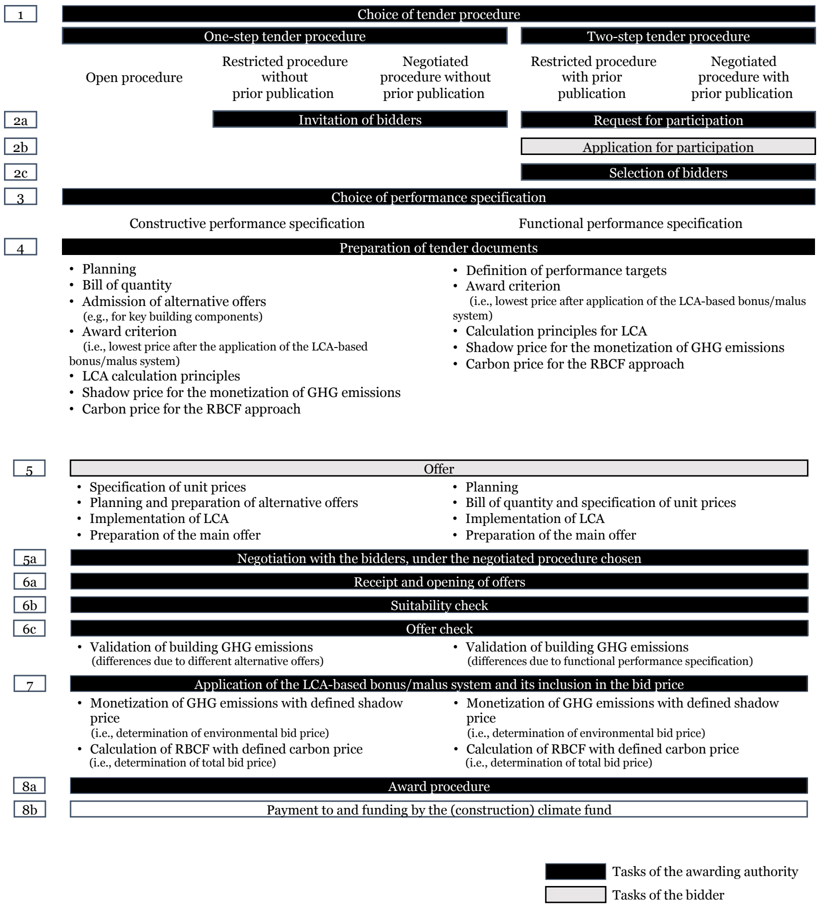


Figure 4.5: Process steps in different tender procedures and the two different performance specifications: (i) tender with constructive performance specifications and (ii) tender with functional performance specifications.

In this context, the first decision, i.e. the choice of tender procedures (steps 1 to 2c), does not yet require any adaptation as a result of applying the LCA-based bonus/malus system.

The second decision, which includes the initial determination of whether the tender should be based on constructive or functional performance specifications (step 3), results in differences in the application of the LCA-based bonus/malus system.

In the case of a tender based on a constructive performance specification, the awarding authority is responsible for the planning of the building and the creation of a detailed bill of quantities, i.e. a bill for the service items including the quantity determination. Based on the tender documents, the bidders calculate their main offers by indicating the unit prices for each service item. In the case of tendering according to constructive performance specifications, no changes or amendments by the bidders are permitted in the tender documents or performance specifications. The federal procurement act, however, allows bidders to propose other innovative or more favourable alternatives in the form of alternative offers in which the know-how of the bidders can be incorporated into the performance specifications (steps 4 to 5a).

Within the framework of a call for tenders with a functional performance specification, the awarding authority must specify the performance target according to the federal procurement act (Section 103 (3) and Section 104 (2)). On the basis of the specified performance target, bidders are responsible for planning the building and preparing the main offer, i.e. the bill of quantities and the unit prices. By applying tenders with functional performance specifications, innovative ideas and bidder know-how can be considered (steps 4 to 5a).

Regardless of the type of performance specification chosen, the awarding authority must transparently define suitability, selection and award criteria in the tender documents. For the application of the LCA-based bonus/malus system, the award criterion must be the lowest PCC scenario.

To enable bidders to perform LCA and LCC, all calculation principles must be specified in the tender documents. Thus, all necessary calculation parameters for the performance of the LCA, such as life cycle modules, RSP, databases for background data, calculation software, and data sets for the energy mix, must be defined.

Furthermore, all calculation parameters to calculate life cycle costs must be defined, including the inflation rate, escalation rates and energy prices. Moreover, the level of the applied carbon price instruments, i.e. the shadow price and the RBCF carbon price, must be specified in the tender documents.

After receipt of the bids and the prescribed offer checks, the bidders' LCA calculations must also be verified when applying the LCA-based bonus/malus system. After validation of the results, the GHG emissions are monetized into external costs using carbon pricing instruments and then internalized in the bid price (steps 6a to 7).

The award is finally made based on the most cost-effective PCC scenario. The payment flows of the GHG emissions bonus or malus are handled by a (construction) climate fund (steps 8a to 8b). The amount of the payments mainly depends on the RBCF carbon price.

Implementation measures

Specific measures are necessary for the implementation of the developed LCA-based bonus/malus system to enable the application of the theoretical approach in the procurement practice.

These required measures can be classified into the following three sets of measures:

1. the set of measures within public procurement law,
2. the set of measures within the LCA methodology, and
3. the set of measures within the monetization procedure.

Table 4.1 shows the three measure sets for the implementation of the LCA-based bonus/malus system and their individual measures.

Table 4.1: Measures sets for the implementation of the LCA-based bonus/malus system and their individual measures.

Set of measures	Individual measures
Set of measures within public procurement law	Definition of the type of the applied performance specification
	Permission of alternative offers during tendering based on a constructive performance specification
	Definition of an appropriate GHG reference value that uses the functional equivalent as an environmental exclusion criterion
	Definition of the LCA-based bonus/malus system as a cost model for the award criterion
	Definition of the applied carbon pricing instruments and their exact values (e.g. shadow price and results-based climate finance approaches)
	Definition of required calculation principles
Set of measures within LCA methodology	Definition of the applicable standards, i.e. ÖNORM EN 15978 and ÖNORM EN 15804
	Definition of a freely accessible applicable database
	Definition of applicable data sets (e.g. use of local data sets like Austrian energy mix and the Austrian district heating mix)
	Declaration of considered life cycle modules according to ÖNORM EN 15804
	Definition of calculation requirements for the individual life cycle modules definition of the reference study period (e.g. 50 years) definition of the replacement cycles based on service life catalogues definition of the energy demand calculation (e.g., based on heating and cooling loads) definition of the assumptions used in end-of-life modules
	Definition of the considered environmental indicators (e.g. GWP in $kgCO_2eq$)
Set of measures wthin monetization	Definition of carbon pricing instruments
	Calculation principles for the external cost based on GHG emissions and shadow price
	Calculation principles for the GHG emissions bonus/malus based on GHG emissions deviation from the GHG emissions mean value of all bids and the RBFC approach
	Internalization of external cost in the bidding prices

4.3 Impact of carbon pricing instruments on the award decision of buildings

After the theoretical framework of the LCA-based bonus/malus system was designed, the next objective was to test the practical application and thus validate the developed process model.

While thesis publication 2 analysed the application of the LCA-based bonus/-malus system through an instrumental modelled case study (see Tables 4.2 to 4.6), the validation of the process model in thesis publication 3 and thesis publication 4 was applied based on a collective case study (see Figures 4.6 to 4.9).

Furthermore, in thesis publication 4, the environmental break-even points, i.e. the carbon prices necessary to change the award decision to that of a more environmentally friendly scenario, were identified (see Table 4.7).

Application of the LCA-based bonus/malus system: An instrumental case study

The assumptions of the instrumental case study are presented in Table 4.2.

The seven submitted bids displayed contain the bid price and an evaluation of the environmental performance, i.e. GWP in $kgCO_2eq/m^2_{NFA}a$. Considering an RSP of 50 years and applying equations 3.1 and 3.2, the external costs and thus the eLCC were calculated for two scenarios, i.e. that with a shadow price of 50 €/tCO_2eq and that with a shadow price of 400 €/tCO_2eq.

Table 4.2: Assumptions in the instrumental case study for the application of the LCA-based bonus/malus system.

Bid price in €		GWP in $kgCO_2eq/m^2_{NFA}$ a	GWP in tCO_2eq	Shadow price scenario 1 in €/tCO_2eq	Shadow price scenario 2 in €/tCO_2eq	External cost scenario 1 in €	External cost scenario 2
Bid price 1	10.370.041	23	5.750	50	400	287.500	2.300.000
Bid price 2	9.020.200	24	6.000	50	400	300,000	2.400.000
Bid price 3	9.433.478	26	6.500	50	400	325,000	2.600.000
Bid price 4	10.821.849	18	4.500	50	400	225,000	1.800.000
Bid price 5	10.068.947	22	5.500	50	400	275,000	2.200.000
Bid price 6	9.433.273	15	3.750	50	400	187.500	1.500.000
Bid price 7	10.811.394	20	5.000	50	400	250.000	2.000.000

Tables 4.3 and 4.4 show the eLCC for the seven submitted bids and the share of external costs compared to that of the initial bid prices.

After the mean value of the GHG emissions of all seven submitted bids was calculated, the deviation in the GHG emissions values of the individual bids from the mean value was calculated.

Table 4.3: Bid prices$_{ENV}$, i.e. eLCC, and their share of the initial bid prices for the seven submitted bids obtained by calculating the external costs at a shadow price of 50 €/tCO_2eq.

Bid price in €		GWP in kgCO_2eq/m²$_{NFA}$ a	GWP in tCO_2eq	External cost scenario 1 in €	Bid price $_{ENV}$ in €	Share external cost / bid price in %
Bid price 1	10.370.041	23	5.750	287.500	10.657.541	3
Bid price 2	9.020.200	24	6.000	300,000	9.320.200	3
Bid price 3	9.433.478	26	6.500	325,000	9.758.478	3
Bid price 4	10.821.849	18	4.500	225,000	11.046.849	2
Bid price 5	10.068.947	22	5.500	275,000	10.343.947	3
Bid price 6	9.433.273	15	3.750	187.500	9.620.773	2
Bid price 7	10.811.394	20	5.000	250.000	11.061.394	2

Table 4.4: Bid prices$_{ENV}$, i.e. eLCC, and their share of the initial bid prices for the seven submitted bids obtained by calculating the external costs at a shadow price of 400 €/tCO_2eq.

Bid price in €		GWP in kgCO_2eq/m²$_{NFA}$ a	GWP in tCO_2eq	External cost scenario 2 in €	Bid price $_{ENV}$ in €	Share external cost / bid price in %
Bid price 1	10.370.041	23	5.750	2.300.000	12.670.541	22
Bid price 2	9.020.200	24	6.000	2.400.000	11.420.200	27
Bid price 3	9.433.478	26	6.500	2.600.000	12.033.478	28
Bid price 4	10.821.849	18	4.500	1.800.000	12.621.849	17
Bid price 5	10.068.947	22	5.500	2.200.000	12.268.947	22
Bid price 6	9.433.273	15	3.750	1.500.000	10.933.773	16
Bid price 7	10.811.394	20	5.000	2.000.000	12.911.394	18

Finally, the PCC scenarios were determined by applying equations 3.3 and 3.4. The GHG emissions bonus/malus and the PCC scenarios were calculated in the first scenario using a RBCF carbon price of 50 €/tCO_2eq (see Table 4.5) and in the second scenario using a RBCF carbon price of 400 €/tCO_2eq (see Table 4.6).

Regarding the award decision, the most cost-efficient based on the unit prices in the bill of quantities is bid 2 (see Table 4.2).

However, among the bids, bid 2 also has the highest GHG emissions. When considering eLCC at a defined shadow price of 50 €/tCO_2eq, bid 2 remains the most cost-efficient (see Table 4.3).

Table 4.5: PCC scenarios and their share of the bid prices$_{ENV}$ for the seven submitted bids obtained by calculating the external costs and the GHG emissions bonus/malus at a shadow price and RBCF carbon price of 50 €/tCO_2eq.

Bid price $_{ENV}$ in €		GWP in tCO_2eq	Deviation GWP to GWP mean value in tCO_2eq	GHG emissions bonus/malus in €	Bid price $_{TOT}$ in €	Share GHG emissions bonus/malus / bid price $_{ENV}$ in %
Bid price $_{ENV}$ 1	10.370.041	5.750	464	23.214	10.680.755	0
Bid price $_{ENV}$ 2	9.020.200	6.000	714	35.714	9.355.914	0
Bid price $_{ENV}$ 3	9.433.478	6.500	1.214	60.714	9.819.192	1
Bid price $_{ENV}$ 4	10.821.849	4.500	-786	-39.286	11.007.563	0
Bid price $_{ENV}$ 5	10.068.947	5.500	214	10.714	10.354.661	0
Bid price $_{ENV}$ 6	9.433.273	3.750	-1.536	-76.786	9.543.987	-1
Bid price $_{ENV}$ 7	10.811.394	5.000	-286	14.286	11.047.108	0

Table 4.6: PCC scenarios and their share of the bid prices$_{ENV}$ for the seven submitted bids obtained by calculating the external costs and the GHG emissions bonus/malus at a shadow price and RBCF carbon price of 400 €/tCO_2eq.

Bid price $_{ENV}$ in €		GWP in tCO_2eq	Deviation GWP to GWP mean value in tCO_2eq	GHG emissions bonus/malus in €	Bid price $_{TOT}$ in €	Share GHG emissions bonus/malus / bid price $_{ENV}$ in %
Bid price $_{ENV}$ 1	12.670.541	5.750	464	185.714	12.895.755	1
Bid price $_{ENV}$ 2	11.420.200	6.000	714	285.714	11.305.914	3
Bid price $_{ENV}$ 3	12.033.478	6.500	1.214	485.714	12.519.192	4
Bid price $_{ENV}$ 4	12.621.849	4.500	-786	-314.286	12.307.563	-2
Bid price $_{ENV}$ 5	12.268.947	5.500	214	85.714	12.054.661	1
Bid price $_{ENV}$ 6	10.933.773	3.750	-1.536	-614.286	10.318.987	-6
Bid price $_{ENV}$ 7	12.911.394	5.000	-286	-114.286	12.397.108	-1

At a shadow price of 400 €/tCO_2eq, this ranking changes, and bid 6 exhibits the lowest eLCC in this context (see Table 4.4).

To lower the shadow price and still enable awarding the contract to those submitting more environmentally friendly bids, the RBCF approach within the LCA-based bonus/malus system is applied, and the PCC scenarios are calculated.

At a defined shadow price and a defined RBCF carbon price of 50 €/tCO_2eq, there is still no change in the bidding order, but the difference between bid 2 and bid 6 is smaller than in the previous set of calculations (see Table 4.5).

Table 4.6 shows the ranking based on a defined shadow price and RBCF carbon price of 400 €/tCO_2eq. The results show that bid 6 becomes the most cost-efficient bid; thus, its submitter is awarded the contract. The GHG emissions of bid 2 and bid 6 show that by applying the LCA-based bonus/malus system, a GHG emissions saving of approximately 38 percent is achievable.

To avoid double accounting when applying carbon pricing instruments, the PCC scenarios are to be understood as fictitious bid prices, which are only used to explore the award decision.

With a shadow price and RBCF carbon price of 400 €/tCO_2eq, bidder 6 is awarded the contract, and the awarding authority pays the eLCC, i.e. the initial bid price, to the bidder and the external costs based on the shadow price of 400 €/tCO_2eq to the climate fund. Compared to the costs of the initial bid price, this indicates an additional cost of 345.000 €. However, since a more environmentally friendly bid is preferred, a subsidy is available through the GHG emissions bonus in the amount of 141.286 €, which is paid to the awarding authority from an established climate fund. If the favourable PCC scenario is environmentally worse than the mean GHG emissions value of all submitted bids, then the awarding authority has to pay the eLCC, i.e. the initial bid price, to the bidder and the external costs and the resulting GHG emissions malus to the climate fund.

Application of the LCA-based bonus/malus system: A collective case study

As a prerequisite for applying the LCA-based bonus/malus system, LCA and LCC were conducted in thesis publication 3 for each of the 37 submitted bids based on the bill of quantities.

The results are presented in Figure 4.6. On the x-axis, the 37 scenarios are shown; on the left y-axis, the GHG emissions are shown and on the right y-axis, the costs are shown.

In the considered collective case study, scenario $B_{25} - E_{14} - P$ (25 cm brick construction, 14 cm EPS insulation and pellet heating) shows the lowest construction costs and GHG emissions of 236 tCO_2eq.

The life cycle costs are lowest for scenario $B_{50} - 0 - \mathrm{H_{gw}}$ (50 cm brick construction, no thermal insulation, and a heat pump), with GHG emissions of 208 tCO_2eq. In summary, this means that awarding the contract according to LCC results in a reduction in GHG emissions of approximately 12 percent.

In Figure 4.7a, the eLCC of the 37 building scenarios are calculated based on a shadow price of 50 €/tCO_2eq. The results show that there are no further GHG emissions reductions possible because the lowest eLCC scenario is identical to the lowest LCC scenario. This indicates that the defined shadow price is set too low to change the award decision to a more environmentally friendly scenario.

Figure 4.7b highlights the PCC scenarios after the application of the LCA-based bonus/malus system based on a shadow price and RBCF carbon price of 50 €/tCO_2eq.

Awarding by PCC scenarios at these carbon prices results in a different award decision. The lowest PCC scenario is scenario $Wc_{36,5} - 0 - H_{gw}$ (36.5 cm wood-concrete construction, no thermal insulation, and a heat pump) and results in a

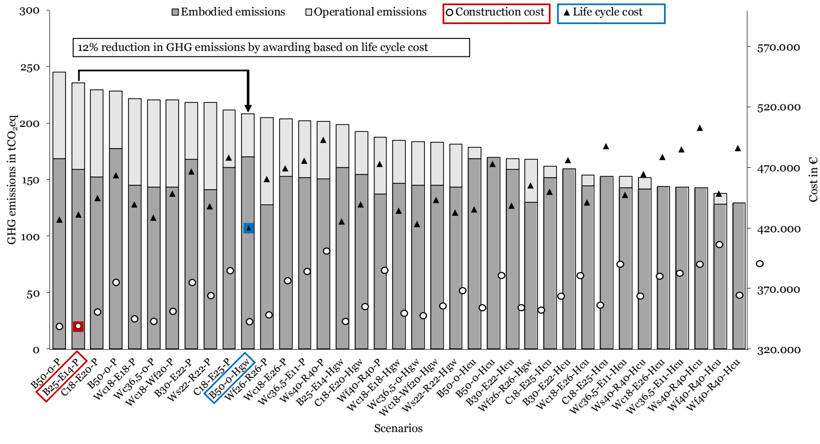


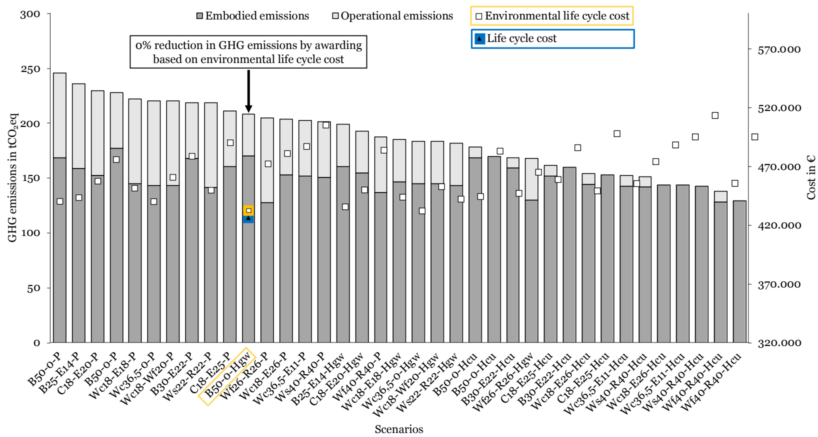
Figure 4.6: GHG emissions (embodied emissions are displayed in dark grey, and operational emissions are displayed in light grey) and costs (construction costs are indicated by white circles and life cycle costs are indicated in black triangles) of the 37 building scenarios. The GHG emissions reduction potential between the lowest construction costs scenario (framed in red) and the lowest LCC scenario (framed in blue) is highlighted.

GHG emissions reduction of 12 percent below that when awarding the contract according to eLCC at a shadow price of 50 €/tCO_2eq and according to LCC.

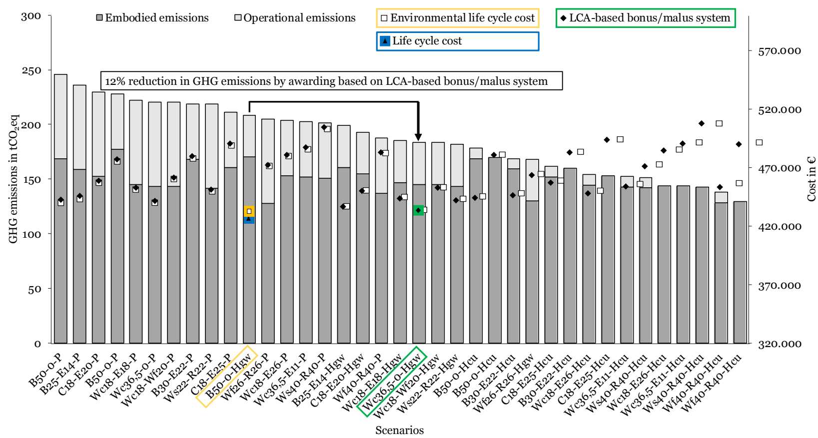
The figure shown in Figure 4.8a presents the calculation of eLCC for the 37 building scenarios under a shadow price of 200 €/tCO_2eq. The results demonstrate that no additional reduction in GHG emissions is achievable between the two scenarios, as the scenario with the lowest eLCC is the same as the scenario with the lowest life cycle costs. This indicates that the defined shadow price is insufficient for initiating a shift towards a more environmentally friendly scenario in the award decision.

The focus of Figure 4.8b is again on the PCC scenarios that result from the implementation of the LCA-based bonus/malus system, using a shadow price and RBCF carbon price of 200 €/tCO_2eq. The results show that in this case, higher carbon prices, i.e. 200 €/tCO_2eq, do not change the award decision from that in the PCC scenarios at lower carbon prices of 50 €/tCO_2eq. Therefore, the increase in carbon prices from 50 €/tCO_2eq to 200 €/tCO_2eq does not result in any further GHG emissions reductions.

Figure 4.9a displays the calculation of eLCC for the 37 building scenarios using a shadow price of 400 €/tCO_2eq. As with the awarding based on PCC scenarios at a shadow price and RBCF carbon price of 50 €/tCO_2eq, the awarding based on eLCC at a shadow price of 400 €/tCO_2eq changes the award decision. Again, compared to the awarding based on LCC, scenario $Wc_{36,5} - 0 - H_{gw}$

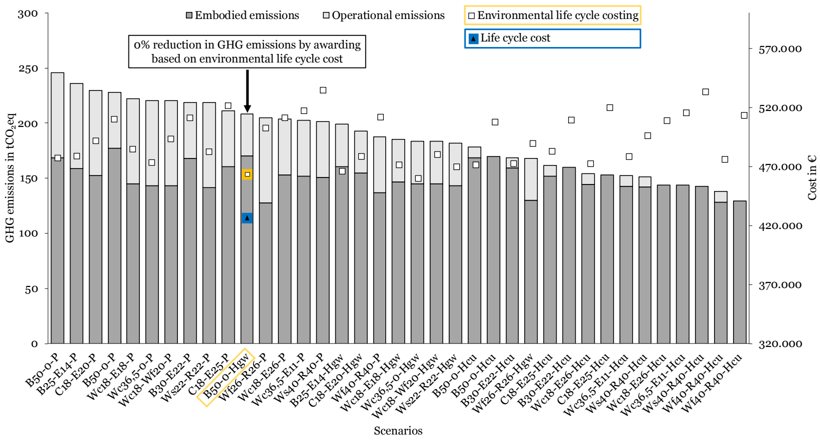


(a) eLCC based on a shadow price of 50 €/tCO_2eq (in white rectangles). The GHG emissions reduction potential between the lowest LCC scenario (framed in blue) and the lowest eLCC scenario (framed in orange) is highlighted.

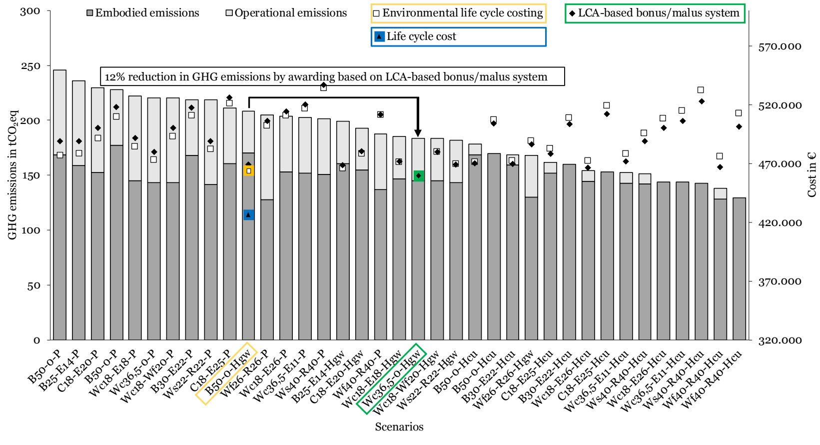


(b) Costs after the application of the LCA-based bonus/malus system based on a shadow price and RBCF carbon price of 50 €/tCO_2eq (black rhombus). GHG emissions reduction potential among the lowest LCC scenario (framed in blue), the lowest eLCC scenario (framed in orange) and the lowest PCC scenario (framed in green) is highlighted.

Figure 4.7: GHG emissions (embodied emissions in dark grey, operational emissions in light grey) and costs (eLCC and PCC scenarios) of the 37 scenarios at carbon prices of 50 €/tCO_2eq.

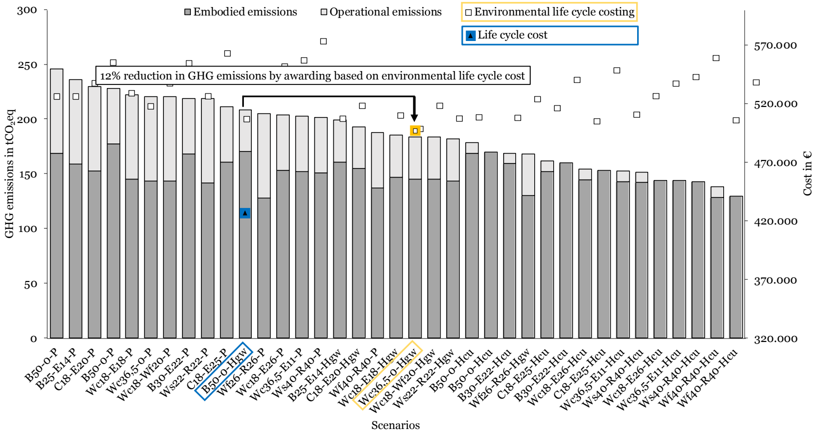


(a) eLCC based on a shadow price of 200 €/tCO_2eq (in white rectangles). The GHG emissions reduction potential between the lowest LCC scenario (framed in blue) and the lowest eLCC scenario (framed in orange) is highlighted.

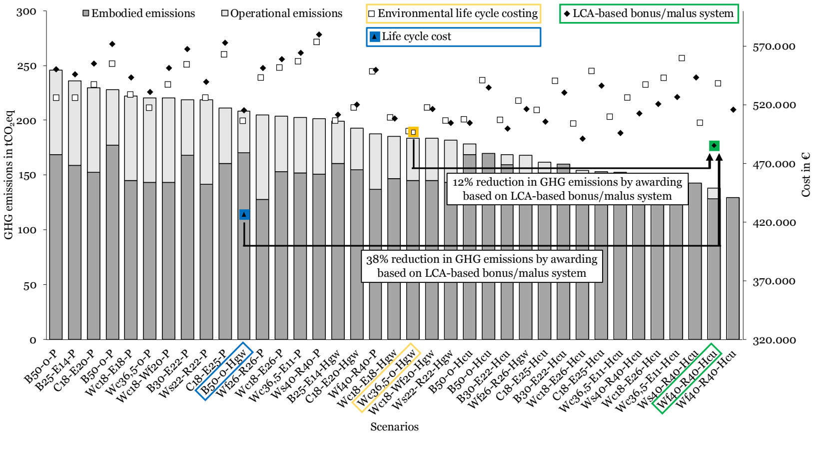


(b) Costs after the application of the LCA-based bonus/malus system based on a shadow price and RBCF carbon price of 200 €/tCO_2eq (black rhombus). GHG emissions reduction potential among the lowest LCC scenario (framed in blue), the lowest eLCC scenario (framed in orange) and the lowest PCC scenario (framed in green) is highlighted.

Figure 4.8: GHG emissions (embodied emissions in dark grey, operational emissions in light grey) and costs (eLCC and PCC scenarios) of the 37 scenarios at carbon prices of 200 €/tCO_2eq.



(a) eLCC based on a shadow price of 400 €/tCO_2eq (in white rectangles). The GHG emissions reduction potential between the lowest LCC scenario (framed in blue) and the lowest eLCC scenario (framed in orange) is highlighted.



(b) Costs after the application of the LCA-based bonus/malus system based on a shadow price and RBCF carbon price of 400 €/tCO_2eq (black rhombus). GHG emissions reduction potential among the lowest LCC scenario (framed in blue), the lowest eLCC scenario (framed in orange) and the lowest PCC scenario (framed in green) is highlighted.

Figure 4.9: GHG emissions (embodied emissions in dark grey, operational emissions in light grey) and costs (eLCC and PCC scenarios) of the 37 scenarios at a carbon prices of 400 €/tCO_2eq.

(36.5 cm wood-concrete construction, no thermal insulation, and a heat pump) is the lowest eLCC scenario and results in a GHG emissions reduction of 12 percent.

A further GHG emissions reduction of 12 percent compared to when awarding the contract according to eLCC at a shadow price of 400 €/tCO_2eq, can be generated by the awarding based on PCC scenarios at a shadow price and RBCF carbon price of 400 €/tCO_2eq. In this case, the bidder proposing scenario $Wf_{40} - R_{40} - H_{cu}$ (40 cm wood-frame construction, 40 cm rock wool insulation and a heat pump) is awarded the contract. The reduction in GHG emissions related to the awarding based on the LCA-based bonus/malus system at carbon prices of 400 €/tCO_2eq is 38 percent.

Environmental break-even points for carbon prices in the collective case study

Since a range of 50 €/tCO_2eq to 400 €/tCO_2eq was assumed for both the shadow price and the RBCF carbon price, a further objective of thesis publication 4 was to analyse the point in the range of carbon prices at which the award decision changes. For the calculation of these environmental break-even points, the shadow price and the RBCF carbon price were increased stepwise by 1 € within their range. Table 4.7 shows the environmental break-even points, the GHG emissions savings potentials and the change in the award decision for the most cost-efficient scenario. For eLCC, awarding the first environmental break-even point occurs at a shadow price of 51 €/tCO_2eq. At this shadow price, the award decision changes from scenario $B_{50} - 0 - \mathrm{H_{gw}}$ to scenario $Wc_{36,5} - 0 - H_{gw}$. The second environmental break-even point occurs at a shadow price of 554 €/tCO_2eq. At this shadow price, the award decision changes from scenario $Wc_{36,5} - 0 - H_{gw}$ to scenario $Wf_{40} - R_{40} - H_{cu}$. For PCC scenarios, the first environmental break-even point occurs at a shadow price and RBCF carbon price of 26 €/tCO_2eq. At these carbon prices, the award decision changes from scenario $B_{50} - 0 - \mathrm{H_{gw}}$ to scenario $Wc_{36,5} - 0 - H_{gw}$. The second environmental break-even point occurs at carbon prices of 277 €/tCO_2eq. At these carbon prices, the award decision changes from scenario $Wc_{36,5} - 0 - H_{gw}$ to scenario $Wf_{40} - R_{40} - H_{cu}$.

Table 4.7: Environmental break-even points in the range of carbon prices (shadow price and the results-based climate finance carbon price) and their effect on the award decision.

Awarding based on	Cost in €	Shadow price in €/tCO_2eq	RBCF carbon price in €/tCO_2eq	Scenario	Compared to scenario	Total GHG emissions in tCO_2eq	GHG emissions reduction potential in %
Construction cost	338.933			B25-E14-P		236	
LCC	422.298			B50-0-H	B25-E14-P	208	12
eLCC	432.580	50		B50-0-H		208	
eLCC	432.760	51		Wc36,5-0-H	B50-0-H	183	12
eLCC	524.947	553		Wc36,5-0-H		183	
eLCC	525.085	554		Wf40-R40-H	Wc36,5-0-H	129	30
PCC	428.063	25	25	B50-0-H		208	
PCC	428.253	26	26	Wc36,5-0-H	B50-0-H	183	12
PCC	473.320	276	276	Wc36,5-0-H		184	
PCC	473.455	277	277	Wf40-R40-H	Wc36,5-0-H	129	30

4.4 Modified planning process for buildings to effectively address the future demands of LCA-optimized planning

Implementing an LCA-optimized planning process for awarding based on eLCC or PCC scenarios requires following a new approach in the early planning phase of buildings to handle the increased requirements and to manage the increasingly complex process. Thesis publication 5 therefore presented the hierarchical reference-based know-why model, which was developed to enhance complexity management in the early planning process for buildings. The model combines the three methodologies of (i) building certification systems (i.e. DGNB), (ii) multicriteria decision making (MCDM) and (iii) systems thinking to successfully integrate sustainability requirements into the early planning phase of buildings. Figure 4.10 shows the framework of the hierarchical reference-based know-why model for the planning of an exemplary building component, i.e. the building envelope.

To apply the hierarchical reference-based know-why model, the model framework encompassing the individual requirements for planning offices must first be developed. After establishing the model framework, the goal of the model is repeated as a means of extending it by including possible planning alternatives. The proposed model comprises the following six general steps:

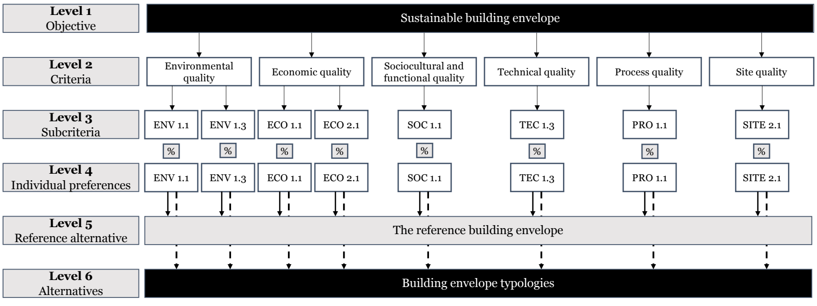


Figure 4.10: Framework of the hierarchical reference-based know-why model for LCA-optimized planning

1. identifying criteria, subcriteria, alternatives and the reference alternative for
   a) defining the relevant certification criteria for buildings,
   b) determining the reference alternative, and
   c) developing planning alternatives
2. decomposing the problem into a hierarchy
3. constructing an assessment matrix using know-why rating
4. conducting the aggregate assessment
5. conducting the weighting computations for the subcriteria
6. calculating the final value of the planning alternatives

The principles of the hierarchical reference-based know-why model can be applied to not only the DGNB building certification system but also all other certification systems. The structure of the model also allows for the evaluation of single construction materials, single building components or whole buildings. For an LCA-optimized planning process, this means that in step 1a, the criterion that must be considered is the environmental quality of the building. The subcriterion is LCA, i.e. ENV 1.1. The basic idea of the hierarchical reference-based know-why model is to compare different planning alternatives with a reference alternative and to highlight the synergies and trade-offs among the sustainability requirements. Therefore, in step 1b, the reference alternative is defined. The reference alternative, e.g. a defined construction material, a defined building envelope or a defined whole building, is rated as zero. This means that the reference alternative is neutral to all defined sustainability requirements. In step 1c, any potential planning alternatives are then designed. In steps 2 and 3, the hierarchical structure of the model is created, and the assessment of the planning alternatives relative to the reference alternative is conducted using the four know-why questions. A planning alternative can be better, equal or worse than the defined reference alternative regarding a particular sustainability requirement, e.g. LCA. In step 4, the assessment results are aggregated. Finally, in step 5, different weightings are considered, i.e. individual stakeholder preferences. If only one criterion is considered, the weighting for this criterion is 100 percent. However, with the hierarchical reference-based know-why model, it is possible to consider more (or all) of the sustainability aspects of the DGNB certification system. In step 6, the final values of the alternatives are calculated.

Figure 4.11 shows a schematic output of the hierarchical reference-based know-why model.

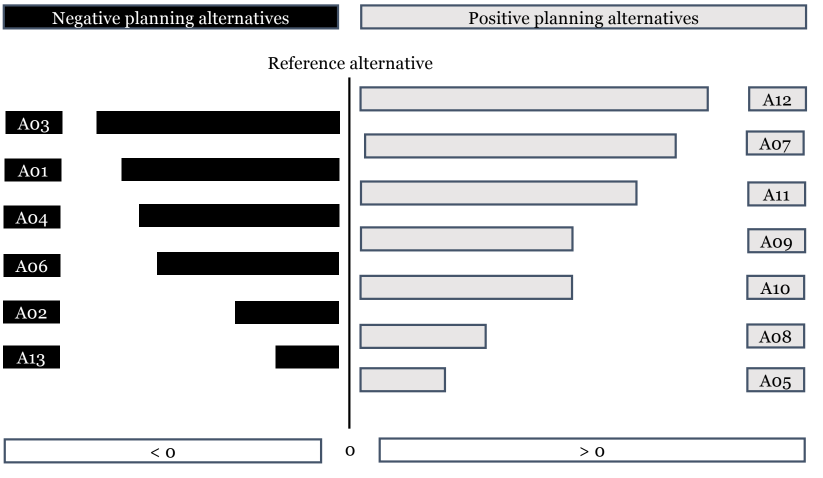


Figure 4.11: Output of the hierarchical reference-based know-why model

The output of the hierarchical reference-based know-why model is displayed as a tornado chart. Negative and positive planning alternatives are separated in this case by a value of zero, i.e. by the reference alternative. Based on the defined sustainability requirements and the defined weighting of the sustainability requirements, the model displays the planning alternatives that are worse than the reference alternative on the left side (in black). Conversely, planning alternatives that fulfil the individual stakeholder preferences better than the reference alternative are on the right side (in grey). This type of representation is possible for all defined criteria. Through this representation, systemic interdependencies among criteria can be accounted for in the early planning process; thus, undesirable developments in the fulfilment of criteria that require planning alternatives can be avoided.

4.5 Summary of major findings

The hypothesis stated at the beginning of this work can be verified by answering the underlying research questions.

The mandatory implementation of LCA in the procurement process of buildings and its internalization as various monetary values contained in bid prices leads to more environmental award decisions. The development and validation of the LCA-based bonus/malus system demonstrates that tendering and awarding based on this cost model can contribute to the decarbonization of the building sector.

The expected additional requirements for LCA-optimized building planning are reduced by applying a systemic planning process, i.e. by the application of the hierarchical reference-based know-why model. The application of this planning model has been shown to make the synergies and trade-offs among planning decisions visible and thus contributes to the achievement of project-specific target requirements and the subsequent reduction in undesirable developments at an early stage.

In thesis publication 1 [222], the application of LCA in the building procurement process was investigated. By conducting a SLR, a final sample of 19 articles was analysed in detail. The results show that LCA is rarely applied in the tendering and awarding process for buildings because of several obstacles, which are further classified into five categories, i.e. (i) methodological obstacles, (ii) organizational obstacles, (iii) governance obstacles[1], (iv) policy obstacles[2] and (v) economic obstacles.

- LCA is rarely applied in the building procurement process.
- There are several inherent (methodological) obstacles to the LCA method.
- The further identified obstacles are a result of applying LCA in the procurement process (organizational obstacles, governance and policy obstacles, and economic obstacles).
- A harmonized framework is needed for LCA implementation in the procurement process for buildings.

In thesis publication 2 [223], an LCA-based bonus/malus system was developed for considering GHG emissions in the award decision of buildings. Within this development, procedural steps for the application of the LCA-based bonus/malus system were proposed, and different levels of carbon pricing instruments, i.e. shadow price and RBCF carbon price, were analysed.

[1] In thesis publication 1, this was initially defined as legal obstacles.
[2] In thesis publication 1, this was initially defined as political obstacles.

- An LCA-based bonus/malus system was developed.
- Minor additions to the tender documents were shown to allow LCA to be implemented in the building procurement process.
- Environmental externalities, i.e. monetized GHG emissions, are included in the bid prices.
- The levels of the shadow price and the RBCF carbon price affect the ranking of bidders.
- The application of the LCA-based bonus/malus system reduces the GHG emissions of buildings.

In thesis publication 3 [224], LCA and LCC were conducted for 37 building scenarios. The life cycle inventories for the calculations were based on functional performance specifications, which resulted in building scenarios that used different construction materials, insulation materials and technical building equipment. The results show that improved energetic standards are connected with decreased operational environmental impacts and additional, slightly higher construction costs.

- Improved energetic standards lead to decreased environmental impacts during the use phase of buildings.
- Embodied emissions significantly differ only between the low-energy housing and passive housing standards.
- Maintaining higher energetic standards results in slightly higher construction costs.
- The low-energy housing standard results in LCC results similar to those of the passive housing standard.

In thesis publication 4 [225], the developed LCA-based bonus/malus system was validated based on 37 building scenarios. Furthermore, different levels of carbon pricing instruments, i.e. the shadow price and RBCF carbon price, were investigated. The results show that when awarding contracts according to LCC and awarding contracts according to eLCC, the environmental impacts of buildings can be reduced. The highest level of GHG emissions reduction can be achieved by awarding contracts according to PCC scenarios by applying the LCA-based bonus/malus system.

- Using an award decision based on cLCC reduces in GHG emissions.
- Further reductions in GHG emissions can be achieved when awarding contracts according to eLCC.
- PCC scenarios can be determined using the LCA-based bonus/malus system.
- Identifying environmental break-even points lowers carbon prices.
- Through PCC scenario awarding, GHG emissions reductions can be achieved at a carbon price of $26/tCO_2$eq.
- Further reductions in GHG emissions can be achieved by awarding according to the PCC scenario when considering higher carbon prices.

In thesis publication 5 [226], a hierarchical reference-based know-why model was developed to consider systemic interactions within LCA-optimized planning. Using a combination of HDM and a systems thinking approach, i.e. the know-why method, the synergies and trade-offs of early planning decisions on project targets, e.g. GHG emissions reductions, can be highlighted.

- A hierarchical reference-based know-why model was developed.
- The holistic planning of buildings requires adopting a systemic approach to all planning practices in the early planning phase .
- Synergies and trade-offs must be communicated at an early phase to all stakeholders involved to prevent subsequent missed objectives.
- After a one-time adaptation of the hierarchical reference-based know-why model to the preferences of the users, the model can be continuously extended by further planning alternatives.

5 Discussion and conclusions

5.1 Originality

With the development of the LCA-based bonus/malus system, the lack of a necessary cost model for considering environmental impacts within the procurement process for buildings has been addressed, and the related research gap has been closed. The detailed step-by-step description of the application procedure for the cost model enables its practical implementation in future tendering and awarding procedures. The validation examples show that the application of the proposed cost model reduces GHG emissions in the building sector. Since new buildings are constantly being tendered and awarded, this reduction effect can be replicated multiple times, culminating in a noteworthy contribution to the decarbonization of the construction industry. Especially in light of the decreasing carbon budget, transforming the building procurement process and thus implementing the cost model represents a promising approach as a further reduction strategy for future policy decisions.

In particular, the associated requirements on the planning side, i.e. future LCA-optimized planning of buildings, which were expected to open another research gap, were addressed through the development of the hierarchical reference-based know-why model. In addition to LCA-optimized planning, the application of the systemic planning model ensures holistic planning, which takes into account other sustainability aspects. The validation of the model shows that the effects of planning decisions on project requirements can be determined in the early planning phase, thus ensuring an early steering option to counteract any undesirable project developments.

5.2 Positioning and contextualization

IPCC experts have recognized that humanity is responsible for the rapid increase in global temperature, causing severe human suffering and irreparable damage to fragile ecosystems. To avoid exceeding the global temperature target of 1.5 degrees Celsius, GHG emissions must be drastically reduced and globally brought to net-zero by 2050 [32].

Net-zero emission buildings

With the LCA-based bonus/malus system, the award decision can be steered towards more environmentally friendly buildings and theoretically, if the distance-to-target is known, towards the awarding of contracts to bidders who plan net-zero emission buildings. The adjusting screws are the limit value for GHG emissions to be defined as an exclusion criterion and the determination of the shadow price and the carbon price within the RBCF approach.

However, one of the challenges with the distance-to-target approach is that target values are often based on assumptions and are thus subject to significant uncertainties. Especially within the building sector on a national level, hardly any reliable distance-to-target values are currently available because of, e.g. missing building stock models. While countries such as Denmark and Switzerland have already established carbon budgets for their national building stock, the budget allocation method does not account for the cross-sectoral and international nature of the life cycle emissions of the national building stock [227]. In addition, current building stock models are insufficiently detailed to use to develop uniformly recognized benchmarks for both the limit and target values of environmental impacts [228].

In this context, different building stock model approaches were analysed, and it was concluded that current studies are limited regarding the number of archetypes, building parts, life cycle phases and environmental indicators covered. Furthermore, the literature suggests that the existing models need to be further developed to effectively support the EU policy on the decarbonization of buildings [228].

Derived from the benchmarking of environmental indicators needed for buildings and the distance-to-target to satisfy the climate targets, the extent of the measures necessary to reduce building emissions depends on various factors. However, it must be mentioned that the current target values are still too high to achieve the needed climate targets [229].

Regardless of the necessary measures, it is important that buildings be designed in such a way that they do not have any undesirable consequences for the climate over their life cycles. Therefore, buildings should be implemented as net-zero emission buildings, i.e. buildings without operational GHG emissions or with at least a neutral balance regarding GHG emissions [80, 230, 231].

Assessment of the environmental performance of buildings

The study of Röck et al. states that *'recent studies have highlighted the role and increasing importance of LCA in EU policy making. In addition, LCA is listed as a policy support tool in the Better Regulation Toolbox, an EU initiative to improve the policy process'* [232].

Furthermore, within the procurement of buildings, EU directive 2014/24/EU on public procurement proposes the use of the LCA method to calculate the external costs within the LCC and suggests using the LCC or other cost models as the criterion for awarding construction contracts for buildings [50].

The LCA method is still rarely applied in the building procurement process, as noted by Parikka-Alhola and Nissinen in 2012 and confirmed by the studies of Cheng et al. and European Commission et al. [233, 234, 235].

This is partly due to challenges in the LCA method and partly due to challenges associated with the transformation of the tendering and awarding process necessitated by the implementation of LCA [222].

One of the main problems is the availability and quality of the required data. Obtaining accurate and reliable information on material inputs, energy consumption, emissions, and waste generation at different stages of the life cycle of buildings can be difficult, especially when multiple stakeholders, complex supply chains, or proprietary information are involved [236].

Regarding data quality assurance, a recent study investigated applying the machine learning method to analyse EPDs and their data quality [237]. Furthermore, a guidance was developed for data collection in the life cycle inventory stage. Nevertheless, a harmonized guideline for the implementation of LCA at the federal level is needed, especially regarding methodological obstacles [238, 239].

First, it is proposed that either existing databases be harmonized or a new database dedicated to building procurement be created, with public access and data accuracy overseen by relevant federal government departments. Second, a special software tool for calculating environmental impacts that is adapted to the Austrian procurement process for buildings is proposed. This is accompanied by the establishment of a dedicated LCA department for transparent and consistent procurement, complemented by an advisory office to educate users about the database and software during the tendering and awarding process for buildings.

Another challenge is determining the system boundaries and scope for an LCA study. It is difficult to determine the processes and impacts that should be included or excluded from such a study. Establishing consistent and representative boundaries requires careful consideration and may involve subjective assessments [236, 240]. In this context, guidelines already exist for defining the RSP and system boundaries of building LCAs [241].

The interpretation and impact assessment of the LCA results create another challenging issue. LCA involves complex modelling and analysis techniques for assessing environmental impacts in various categories, such as climate change, resource use, and toxicity. Selecting appropriate impact assessment methods and indicators and interpreting the results in a meaningful way require assigning weights and values to different impact categories [242]. Support for the impact assessment stage, e.g. for the EU Level(s) framework, can be found in the study of De Wolf et al. [243].

Uncertainty and variability represent another challenging area. The results of an LCA are subject to uncertainty and variability caused by data gaps, simplifications in modelling, and methodological choices. The adequate treatment and quantification of uncertainty and variability is critical for making reliable decisions [244].

Sensitivity analyses and Monte Carlo simulations are often used to assess the robustness of LCA results [245]. The study of Marsh, Allen, and Hattam explored the uncertainties in building LCAs and derived recommendations for tackling them [246].

This doctoral thesis does not aim to provide solutions to methodological challenges but instead focuses on the implementation of LCA in the building procurement process. While it briefly acknowledges methodological obstacles related to LCA, it refrains from conducting sensitivity analyses or Monte Carlo simulations, as its primary focus is on the practical implementation of LCA rather than methodological exploration.

Monetization of environmental indicators

In addition to the challenges faced when using the LCA method to assess the environmental impacts of buildings, challenges also exist related to the level of carbon prices when monetizing environmental impact into external costs.

Regarding determining the level of a shadow price and other internal carbon prices, such as the RBCF carbon price, no scientific consensus has yet been reached on how to do so. Defining a certain level for a shadow price can be a difficult task, as there are various factors that can influence its value.

However, determining the appropriate level for shadow prices can be challenging due to the subjective nature of the required calculation. Such a calculation requires a thorough understanding of the specific context, the relevant stakeholders, and the potential trade-offs among different resources [247, 248, 249].

In this context, the level of the currently fixed CO_2 price is often discussed. The German Federal Environment Agency has calculated that the costs to society of emitting CO_2 and other GHG emissions are 195 €$/tCO_2$eq today and will be 250 €$/tCO_2$eq in 2050; however, only if the welfare of current generations is valued higher than that of future generations. If welfare is valued equally across generations, the societal costs of CO_2 and other GHG emissions would be 680 €$/tCO_2$eq today and 765 €$/tCO_2$eq in 2050 [250].

Additionally, a clear position is taken by the association CEOs FOR FUTURE, emphasizing the inevitability of implementing CO_2 pricing for all sectors of the economy and society from an economic standpoint [251].

To ensure that companies also invest in sustainable technologies in Austria a recent study from the Austrian Institute of Economic Research also advocated for a higher CO_2 price. The study assumes that approximately 300 €$/tCO_2$eq are needed to create an incentive [252].

The need for higher carbon prices is also confirmed by this doctoral thesis. The case studies have shown that in the considered range, i.e. 50 to 400 €/tCO_2eq, the award decision can be influenced. Depending on the awarding model, the calculated environmental break-even points are at 26 €/tCO_2eq, 51 €/tCO_2eq, 277 €/tCO_2eq or 554 €/tCO_2eq.

Moreover, carbon prices can also significantly influence the amount of subsidies received from the proposed establishment of a (construction) climate fund and the amount of the relevant project-related penalties.

A defined carbon budget can be used to avoid the necessity of determining carbon prices on a case-by-case basis. However, this approach entails two further difficulties. First, there are still no carbon budget values for individual building types in Austria. Second, the award criterion 'carbon budgets' must be weighted in relation to the price. In the context of determining carbon budgets, benchmarks for kgCO_2eq/m^2 of building area are set in the literature; however, these are not adapted to the climate target paths necessary for achieving our climate targets.

Apart from the difficulties already mentioned, another option could be to develop mandatory carbon budgets for new buildings as a function of property size (cf. building density). This alternative approach also avoids the need to internalize the external costs of environmental impacts. As in mandatory compliance with building density, these values can be individually adapted.

Transformation of the building procurement process

The action plan for sustainable public procurement (German: Aktionsplan nachhaltige öffentliche Beschaffung) (naBe) is a federal initiative of the Federal Ministry for Climate Action, Environment, Energy, Mobility, Innovation and Technology in Austria. The naBe action plan has three main goals, all of which are to be realized within the legal framework of the federal procurement act. First, sustainable procurement is to be established in all federal institutions. Second, the plan aims to harmonize the criteria for sustainable public procurement. Third, the plan aims to secure Austria's pioneering position in sustainable public procurement within the EU. On the 23rd of June 2021, the federal government adopted the naBe action plan, including the naBe core criteria. This established mandatory implementation by federal institutions from the 1st of July 2021 [253].

Within the building industry, the naBe criteria apply to the new construction and refurbishment of office buildings, educational buildings, and sports and event venues as well as healthcare buildings and hospitals. In the context of considering the environmental performance of buildings, the eco-index (OI3) is proposed. The eco-index (OI3) assesses the environmental impact of the construction of a building based on three environmental impact categories (global warming potential, acidification potential and nonrenewable primary energy demand), which are combined into a single characteristic value and are therefore not consistent with the standards developed by CEN/TC 350. Further differences in standardization can be found regarding the assessment boundaries [254].

Although the LCA-based bonus/malus system recommends the valuation of GWP by LCA using the standards of CEN/TC 350, the developed cost model can also be applied based on the eco-index (OI3), as long as monetization values for the eco-index (OI3) are specified.

However, particularly when the environmental assessment of buildings becomes mandatory, enterprises must promote the training of employees and the generation of know-how in the field of LCA to remain competitive in the market [255].

Although there are already guidelines for the application of LCA in the literature [256, 257, 258, 259], none exist for the implementation of LCA in the procurement process for buildings to support individual enterprises.

In addition to the necessary adaptations at the organizational level of enterprises, further developments are needed at the technical level. The adaptation and development of sustainable and innovative solutions across all disciplines helps reduce environmental impacts and increases competitiveness.

Furthermore, to transform the procurement process and to implement an LCA-optimized planning process, adapted remuneration models and subsidies are needed [39].

The awarding authorities must account for not only the construction costs but also the life cycle costs in the budget negotiations for projects to ensure the life cycle-oriented planning and execution of buildings.

For this reason, to implement the developed LCA-based bonus/malus system, the establishment of a (construction) climate fund is proposed. On the one hand, external costs and project-related penalties (GHG emissions malus) can be paid into this fund. On the other hand, GHG emissions bonuses can be paid out to the awarding authorities from this fund. Moreover, the fund can also be used to handle environmental compensation measures in the postprocurement phase. In addition, a combination of (construction) climate funds and funding measures in the area of refurbishment could be useful.

In addition to attention to the procurement process itself, considering the preprocurement and postprocurement phases is critical to fully leveraging the potential of procurement in pursuing decarbonization goals in the building sector.

An environmental management review is therefore proposed in the preprocurement phase. This review is meant to be carried out in conjunction with the introduction of a sustainability assessment to be performed as a needs and alternatives assessment prior to an award, in which the needs and basic conceptual options are elaborated. The public should be given the opportunity to comment on the planned procurement [260].

In the postprocurement phase, possibilities exist for monitoring and sanctioning sustainability deficits. However, the danger is merely monetizing sustainability deficits, e.g. through penalties, which compensate the financial disadvantage of the public sector and not for the environmental deficit. One remedy for this could be imposing an environmental compensation obligation in the case of underperformance, which can already be mapped contractually. Basically, two types of compensation measures should be considered. First, the sustainability deficit should be eliminated at the level of the tendered object itself, e.g. through technical retrofits of the building. If this is not possible, a compensation payment for environmental compensation measures related to other objects is needed. It is important that the use of funds from such compensation payments be as specific, timely and traceable as possible. The fund into which such payments flow must be designed with strict earmarking and proof of use [260].

Requirements for LCA-optimized planning

The requirement of reducing the GHG emissions of buildings, which exerts additional systemic effects on other building performance areas, e.g. building physics, user comfort, and costs, increases the complexity of the planning process and therefore makes it more error-prone. To manage this increased level of complexity, an adapted planning process that supports the early consideration of synergies and trade-offs within planning decisions is needed.

The use of the developed hierarchical reference-based know-why model provides a way to semiquantitatively assess different planning alternatives and contrast their impact on required sustainability goals. The DGNB certification system was chosen for the development of the hierarchical reference-based know-why model, as it is a frequently used performance-based building certification system in Austria, Germany, and Switzerland. However, the hierarchical structure of this model can also be based on other building certification systems or frameworks.

An added value of the developed model is that it can be adapted to the specific needs of the user. This means that after the initial creation of the model structure, the model can be used as a planning aid for not only entire buildings but also individual building components and construction materials.

This also makes it possible to derive enhancement strategies for buildings and individual building components. It also becomes clear that the achievement of defined sustainability goals, such as GHG emissions reduction, is not a singular optimization problem but rather requires a holistic approach. In addition to using a systemic planning model, the maturity assessment method is suggested for the quality assurance of planning decisions [261].

Moreover, the hierarchical reference-based know-why model not only makes the complexity of systemic planning manageable but also creates an internal enterprise database containing empirical values that can be used for future projects. Based on these empirical values, the pace of decision making can be accelerated in the future. In addition, the model can be used as a calculation tool since the planned or invoiced costs can also be included for all planned alternatives.

Regarding the estimation of external costs, different carbon prices can be defined within the planning variants; thus, an awarding process according to the LCA-based bonus/malus system can be supported. These advantages regarding future time reductions in the planning phase and offer preparation compensate for the additional time needed for the creation of the model. However, the question of the practical application of the developed systemic planning model remains.

The know-why method can be used to model any ideas or strategies related to complex projects, processes, economic development, the environment, society, life planning and much more. Worldwide, well-known companies (from BMW to Telekom), institutions (from the German Armed Forces to the Federal Environmental Agency), individual consultants, schools and universities are already using this method.

For the application of know-why questions in the planning process for buildings, the method was adapted and validated in a research project and in studies. A practical application has not yet been implemented. Nevertheless, the development of a broad and accepted application of this new systemic planning approach can be compared with past already established innovative methods such as 3D building modelling or building information modelling (BIM). These methods were also critically scrutinized after their development and first applications, and today represent the state-of-the-art in the planning process for buildings.

For practical integration into the planning process, applying the hierarchical, reference-based know-why model is recommended for a small building that is put out to tender by an awarding authority such as the City of Graz, which is currently taking notable steps towards decarbonizing the building sector through the development of climate-friendly and sustainable building standards for architectural competitions [262].

Additionally, the model can be used as an external communication tool due to the simplified visualization of the impacts on defined project goals. The aim of the hierarchical reference-based know-why model is not to predict an exact value for the contribution made by the alternatives to the defined sustainability aspects but rather to illustrate, from a holistic perspective, a positive or negative trend induced by certain planning alternatives when compared to a well-known reference case and their importance to the overall project goals.

Other supporting tools related to the visualization of LCA results in the planning process for buildings have been investigated by Hollberg et al. Their study reviewed different visualization options and discussed both recent and potential future developments [263].

Combinations of existing and future tools

The integration of LCA into BIM presents a promising approach to address the sustainability challenges associated with building planning and construction. By incorporating LCA into BIM, designers and stakeholders can assess the environmental performance of buildings at early planning stages and make informed decisions regarding material selection, energy efficiency, and waste management [264, 265]. Regarding the assessment of the economic performance of buildings using BIM, a recent literature review investigated its application [266].

The use of BIM provides a rich database of information and enables the simulation of different planning scenarios, thus allowing for the quantification and analysis of environmental indicators. Through the integration of LCA into BIM, key performance indicators such as GHG emissions, energy consumption, water usage, and waste generation can be dynamically assessed and optimized [267].

Furthermore, the integration of LCA into BIM promotes interdisciplinary collaboration among architects, engineers, contractors, and other stakeholders, fostering a more integrated and iterative planning process. By considering LCA from the early planning stages, potential synergies and trade-offs among different environmental aspects can be identified, resulting in optimized solutions that minimize environmental impacts without compromising functional and aesthetic requirements.

For example, CAALA is a software tool that facilitates the integration of LCA into BIM. This tool imports BIM models and automates the generation of life cycle inventories using its extensive material and process database. The use of CAALA enables comprehensive LCA analyses, including analyses of energy consumption, GHG emissions, and waste generation. Its use supports scenario simulations and the exploration of planning alternatives, empowering stakeholders to make informed decisions early in the planning process. The tool can also be used to consider social and economic aspects, thereby broadening sustainability assessments. Overall, the use of CAALA enhances the efficiency and effectiveness of LCA integration into the BIM workflow, promoting sustainable building practices [268].

However, challenges remain in effectively integrating LCA into BIM. These challenges include the need for standardized and interoperable data formats, accurate and up-to-date life cycle inventory data, and the development of streamlined workflows that allow for efficient LCA analysis within the BIM environment [269, 270, 271].

Another promising approach to future LCA-optimized planning is the use of artificial intelligence (AI) [272, 273]. The connection between AI and the LCA of buildings lies in the ability of AI to automate data collection, analyse complex data sets, support decision making, and enhance modelling accuracy. AI streamlines LCA processes by automating data collection and processing, identifying patterns in environmental impacts, and providing insights to support decision making. Additionally, AI technologies can integrate real-time data, thus improving the accuracy and reliability of LCA models. Overall, AI enhances the efficiency and effectiveness of LCA applications, facilitates informed decision making and promotes sustainable building practices [274].

5.3 Limitations and implications

Although the existence of the research gap described by this work is confirmed by the low number of articles in the final sample of SLR, the 19 articles containing relevant studies are still too few to make a representative statement concerning implementation obstacles.

Despite efforts to develop comprehensive search strategies for performing an SLR, search bias always presents a limitation. In addition to the Scopus and ScienceDirect databases, the use of additional databases such as the Web of Science and Google Scholar reduces some of these limitations, as they cover a broader range of disciplines and may include additional relevant studies.

Furthermore, the specified constraints within an SLR, e.g. the exclusion of grey literature (such as conference proceedings, technical reports, and unpublished theses) and the defined publication period and language of the studies (language bias), represent certain limitations and may restrict the number of relevant studies in the final sample.

Another potential limitation of an SLR is publication bias, which refers to the tendency of authors and journals to report positive results and suppress negative results. To assess the level of publication bias, statistical methods such as funnel plots can be used to examine the relationship between the sample size and effect size of the included studies. If significant asymmetry is observed, it may indicate the presence of publication bias. In the conducted SLR, no statistical methods were used to analyse potential publication bias.

While the aim of an SLR is to provide an objective summary of the available evidence, the quality of the studies included in the review can influence the validity and reliability of the results. This type of bias occurs when the process of selecting studies for inclusion in the review is not objective and is influenced by the reviewers' personal biases or preferences (selection bias).

In this context, one limitation is the fact that quality assessment tools may not be standardized or may not cover all aspects of study quality. This can result in inconsistent judgement among reviewers and the inclusion of low-quality studies in the review (quality assessment bias). To mitigate this limitation, reviewers should use validated quality assessment tools and clearly report the results of the assessment for each included study. To minimize selection bias, reviewers must clearly define their inclusion and exclusion criteria and apply them consistently across all studies. Also important is considering the impact of study quality on the overall results and performing sensitivity analyses to explore the effects of excluding low-quality studies.

To use the SLR, an assessment table for conducting meta-data analysis prior to reviewing the relevant studies was developed. Furthermore, a dual control principle, i.e. two reviewers screening the identified articles and independently excluding them, was used in the exclusion process for the studies. No sensitivity analyses were performed to determine the impact of study exclusion.

The LCA-based bonus/malus system has certain geographical limitations, as the application steps are designed for the federal procurement act and thus are specific to the building procurement process in Austria.

Regarding the mandatory application of the federal procurement act, only public-awarding and sector-awarding authorities are bound by this law. In contrast, private awarding authorities can voluntarily use the federal procurement act as the basis for their contracts but are not obliged to do so. Therefore, the developed LCA-based bonus/malus system first addresses the procurement processes for public buildings by public-awarding authorities in Austria. After the developed LCA-based bonus/malus system for public-awarding authorities is established, it must be adapted and made applicable for use by private awarding authorities. This is of great importance, as private awarding authorities have a decisive influence on construction activities in Austria. The biggest problem in this regard lies in the nonmandatory application of the federal procurement act for private awarding authorities. A slimmed-down form of a public procurement law for such authorities can help address this issue.

In addition, the application of the LCA-based bonus/malus system can cause certain difficulties when comparing the offers depending on the performance specifications. From the perspective of tendering on the basis of a functional performance specification, comparing offers is difficult since the bidders are responsible for the planning of buildings. Therefore, in Austrian tendering practice, a constructive performance specification is usually the basis for tendering. Regarding model application, alternative offers are meant to be permitted during the tendering process on the basis of the constructive performance specification to give the bidders an opportunity to contribute their know-how in the form of innovative and environmentally friendly solutions with the aim of obtaining different levels of environmental performance in the individual offers. Allowing these alternative offers, however, also carries a certain risk to the comparability of the offers.

During the case study validation, LCA and LCC were conducted under 37 different building scenarios. In this context, methodological limitations existed to the conducted LCA and LCC.

The LCA system boundaries were set to cover the life cycle stages of production. (A1-A3), construction (A4-A5), replacement (B4), operational energy use (B6), demolition (C1), transport (C2), waste processing (C3), and disposal (C4). To evaluate the impacts of the production stage (A1-A3) and the observed end-of-life stages (C3, C4), the specifications listed in the bills of quantities were used. Additionally, the environmental impacts of modules A5 and C1 were estimated to be either 5 percent or 2 percent of the impact of the product stage (A1-A3), respectively.

Moreover, the 0/0 approach is considered the most understandable and robust method for the conducted study because it does not account for biogenic carbon from biobased materials. Nevertheless, the 0/0 approach cause discrepancies of up to 30 percent, unlike the dynamic impact calculation method, which is generally considered more reliable, especially for biobased materials [275].

While LCC is performed dynamically, LCA does not account for dynamic developments, such as changes in the energy data records. However, a dynamic LCA can be carried out using the LCA-based bonus/malus system if the necessary calculation principles and data sets are defined in the tender documents.

In addition, no discounting of future emissions was done because the concept of the carbon budget approach is supported, which states that it is irrelevant whether emissions occur now or in the future. An overview and recommendations on discounting in LCA and the consideration of the external costs of environmental impacts can be found in Szalay and Lupíšek [276].

For LCC, ISO 15686-5 was used as the basis of the calculation [89]. The structure of the cost categories is based on ÖNORM B 1801 Part 1 and Part 2 [216, 217]. However, not all cost categories were considered during the calculation. Since construction costs are based on the received bills of quantities, replacement cycles for materials based on service life catalogues over 50 years were assumed and then used in the calculation of the maintenance costs. Although end-of-life costs were not considered in LCC, even if they were considered, no change in the results is expected due to the very small cost difference between the deconstruction and recycling methods of the different construction methods. In addition, end-of-life costs become relatively small compared to construction and operational costs due to discounting over the RSP. For the cost calculations, a dynamic LCC, i.e. the NPV method, was used. This method has limitations related to the defined economic parameters, such as the inflation rate, escalation rates and energy price. The assumed values are based on the values in 2018 and therefore do not account for developments resulting from the COVID-19 crisis or the Ukraine-Russia conflict. In addition, no sensitivity analyses, i.e. step-by-step alterations of the economic calculation parameters, were carried out.

Additionally, the LCA-based bonus/malus system does not conduct a social life cycle assessment (sLCA) as defined in Klöpffer and Grahl [81] or an sLCC as suggested in Ciroth et al. [87]. However, the inclusion of other environmental indicators and their monetization, and the consideration of other sustainability aspects, is possible.

In principle, the LCA-based bonus/malus system is applicable for the procurement of all building typologies. However, the validation of the model was tested on the basis of a modelled instrumental case study on the one hand and on a real case study involving a single family house on the other.

During the modelled instrumental case study, bid prices, i.e. construction costs, and the environmental performance of the bids, i.e. GHG emissions, were assumed based on values in the literature. The cost values are based on BKI [205]. The GHG emissions are within the range of the target and reference value benchmarks of the DGNB building certification system for the office and educational building scheme [31]. The GHG emissions reduction potentials derived from these case studies are not generally valid and differ across different building types. Therefore, further investigation is necessary to assess its impacts on other building typologies, such as multistory residential or nonresidential buildings. While studies already exist on the environmental damage costs of some environmental indicators, and values for their monetization are thus available [118], these values do not exist for all environmental indicators. Furthermore, when considering several environmental indicators simultaneously, the weighting problem must be solved when applying the LCA-based bonus/malus system [277].

In the context of external costs, in this doctoral thesis only GHG emissions were monetized and internalized in the bid price in the validation examples. However, the theoretical framework of the developed LCA-based bonus/malus system enables the consideration of indicators for all other environmental impacts. This requires the definition of monetization values and a weighting of all considered environmental indicators. Due to the difficulties in identifying limit and target values for GHG emissions in Austria using the distance-to-target approach, the level of the defined carbon prices represents a first step towards GHG emissions reduction within the procurement process for buildings.

While the application of internal carbon pricing instruments influences building procurement decisions towards a more environmentally friendly perspective, they also imply certain limitations on their application. Internal carbon pricing instruments such as the shadow price and the RBCF carbon price are voluntarily applicable instruments designed to monetize GHG emissions. This means that each enterprise decides for itself whether to pursue and implement an internal GHG emissions reduction strategy. In this respect, many enterprises strive to impose higher internal economic burdens in terms of investments in the short term, e.g. by applying internal carbon pricing instruments, to pay lower environmental damage costs in the medium and long term, e.g. in the form of ETS certificates or the carbon tax.

To meet the increased requirements of an LCA-optimized planning process, implementing a systemic planning approach is necessary to identify and understand the synergies and trade-offs involved in such a process.

Methodically, the developed hierarchical reference-based know-why model is based on the HDM approach and the DGNB building certification system. However, the theoretical framework of the model can be adapted to other building certification systems or to other needed sustainability criteria. Furthermore, the validation of the model has been conducted on the basis of the building component facade. The model has not been tested regarding its application to other building components or to the building as a whole. However, the hierarchical reference-based model can be applied to other building components or to the entire building.

The principle behind the HDM approach is structuring complex decision problems into hierarchies of objectives, criteria, and alternatives. Within HDM, analytic hierarchy process (AHP) is the most commonly used method. The AHP also breaks down complex problems into hierarchies of criteria and alternatives, allowing decision makers to express preferences through pairwise comparisons. AHP accommodates both quantitative and qualitative factors, ensuring mathematical consistency and aggregating individual preferences into comprehensive rankings.

Due to the hierarchical structure of the DGNB building certification system and the aim of comparing a planning alternative to a reference alternative the principles of AHP are applied.

Nevertheless, next to the AHP there are many other HDM methods such as SMART (the Simple Multi-Attribute Rating Technique), the ELECTRE (Elimination and Choice Translating Reality) method, the PROMETHEE (Preference Ranking Organization Method for Enrichment Evaluations) method or the TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) method. An overview of multicriteria decision making methods for (sustainable) construction can be found in a study by Scherz [278].

5.4 Impact and future recommendations

Awarding construction contracts based on a GHG emissions reduction strategy is beneficial for public-awarding authorities for several reasons. As awarding authorities are responsible for the tendering and awarding of new buildings, the use of the developed cost model can assist in the selection of bidders who are committed to reducing GHG emissions in their construction practices.

First, the awarding authorities of the federal government, e.g. Bundesimmobiliengesellschaft (BIG), of the states, e.g. Landesimmobiliengesellschaft Steiermark (LIG), or of the cities, e.g. Gebäude- und Baumanagement Graz GmbH (GBG), can significantly contribute to achieving the defined climate targets within their areas of competence and responsibility and thus demonstrate their commitment to sustainable practices.

Second, doing so allows them to comply with regulations governing GHG emissions, such as the building codes or emission reduction targets set by government agencies.

Third, it can lead to long-term cost savings, as buildings that are designed and constructed to be energy-efficient can reduce the levels of energy consumption and operating costs.

Finally, public-awarding authorities that prioritize sustainability and environmental responsibility can benefit from a positive reputation among stakeholders, including customers, investors, and the public.

Awarding construction contracts based on the LCA-based bonus/malus system can also benefit bidders in several ways.

First, bidders with expertise in designing and constructing energy-efficient buildings may have a competitive advantage when bidding for contracts that emphasize GHG emissions reductions. This can help them differentiate themselves from their competitors and win more contracts.

Second, bidders may be eligible for funding or incentives from government agencies or private organizations by offering sustainable solutions. This can lower their costs and increase their profitability.

Third, prioritizing environmental responsibility can also improve a bidder's reputation with stakeholders, which can lead to new business opportunities.

Finally, designing and constructing energy-efficient buildings can reduce the risk of incurring future costs associated with energy consumption and maintenance, providing long-term benefits to the client and potentially reducing the bidder's own risk level.

Additionally, for policy makers, prioritizing environmentally friendly solutions in public construction contracts has a positive impact. Policy makers can contribute to the decarbonization of the construction industry, the achievement of climate targets and the commitment to sustainable practices. In addition, sustainable construction can bring economic benefits by creating new jobs and encouraging innovation in the construction industry.

In addition, sustainable construction can have a positive impact on public health by reducing levels of air and water pollution and promoting a healthier living environment. In this context, policy makers can prioritize sustainable solutions to improve public health outcomes and reduce healthcare costs.

New opportunities for research and development are also emerging as a result of the development of the cost model. By prioritizing sustainable solutions in construction contracts, researchers can access new data and opportunities to study the environmental impact of construction and develop new, innovative solutions. Researchers can access new research and funding opportunities and collaborate with bidders and awarding authorities. Therefore, working with bidders and awarding authorities on sustainable construction projects can help researchers ensure that their research has a real-world impact. Additionally, through the application of the LCA-based bonus/malus system, the prerequisites for the implementation of a net-zero built environment can be taught in all areas of education, ultimately helping achieve climate goals and creating even stronger stakeholder awareness of the importance of GHG emissions reduction.

However, in addition to the impacts discussed in this doctoral thesis, some future challenges exist for mandatory LCA implementation in the procurement process for buildings.

The following lists, which are based on the IEA EBC Annex 72 findings [131], highlight the identified future recommendations, that are mapped to the spheres of influence of the various stakeholders. The recommendations were expanded and particularly important points for the implementation of the LCA-based bonus/malus system) were highlighted in bold.

Government and administration

- **Develop legally binding limit and target values for GHG emissions**.
- Develop a legally binding minimum benchmark for biogenic carbon.
- **Mandatory monitoring of environmental impacts of buildings.**
- **Establish a construction climate fund to handle project-related funding due to environmental overperformance and charges due to environmental underperformance.**
- Support research programs on benchmark development for environmental indicators.
- Support research programs on sustainable construction and construction materials and building technology with environmental impacts.
- Support research programs on negative emission technologies.
- Specify international and national standards to ensure consistency among the LCA in the construction sector.
- Develop a harmonized LCA database for the construction sector.
- Develop a harmonized LCA software for the building procurement process and the construction sector in general.
- Improve education on sustainable construction and, in particular, on solutions to avoid construction-related environmental impacts.
- **Provide guidelines for the implementation of LCA within the building procurement process.**
- **Pay project-related bonuses in the case of environmental overperformance and charge project-related fees in case of environmental underperformance.**

Investors, banks and financial institutions

- **Demand the integration of an assessment of GHG emissions, environmental impacts and resource consumption in the building planning stages as relevant decision criteria.**
- Invest in building projects with low GHG emissions, environmental impacts and resource consumption.
- Demand the quantification of GHG emissions, environmental impacts and resource consumption as a basis for risk assessment and economic valuation.

Research organizations

- Offer mandatory/obligatory courses on LCA and its application in the building sector and its suppliers.
- **Develop limit and target values of GHG emissions for the Austrian building sector.**
- Promote research programs on carbon pricing instruments.
- Establish a knowledge/information centre on sustainable construction.
- Train engineers and architects to plan with low carbon building materials and to plan buildings with low GHG emissions, environmental impacts and resource consumption.
- Offer courses on negative emission technologies in process engineering and forest management.

Designers, architects and engineers

- Discuss planning targets, challenge client briefs on the size and comfort of building project, support clients in setting targets.
- Identify options to reduce the environmental impacts of building projects through design, structure, and materials by using a systemic approach.
- Consider the renovation of existing buildings as a relevant alternative to demolition following new construction.
- **Assess the different planning alternatives with LCA.**
- **Calculate the external costs of planning alternatives to minimize project-related penalties.**
- Identify and realize solutions to increase the adaptability and longevity of buildings.
- Apply circularity principles using local, recycled, and low-impact materials; plan building elements for easy disassembly and reuse.
- Strive for lowering operational energy demand and covering the remaining demand with energy from renewable sources.
- Use advanced tools to quantify GHG emissions, environmental impacts, and resource consumption throughout the building project's planning

process for continuity and accuracy.
- Periodically attend further education courses on sustainable construction.

Operators of EPD programs, sector specific LCA database, certification schemes and labels

- **Follow international standards on environmental life cycle assessments.**
- Ensure that product, use and end-of-life stages are included and consider also including transport to construction sites and construction.
- **Require a single life cycle inventory database for LCA of all construction products and systems; allow use of other databases in exceptional cases.**
- Exercise caution with environmental credits attributed to the building, especially if borrowed from future generations or third parties; eliminate any potential double counting of these credits.
- Consider method, data, tools, benchmarks, and targets as interdependent elements for the consistent and reliable assessment of environmental impacts and resource consumption related to buildings.
- **Introduce binding targets for life cycle GHG emissions and environmental impacts of buildings, with a roadmap to net-zero by 2035. Include a separate target for resource consumption to prevent burden shifting.**
- Prioritize using absolute rather than relative target values defined against a virtual reference building.
- Consider implementing a minimum benchmark for biogenic carbon content in buildings, considering local availability, building tradition, and suitability. This can help maintain or increase the amount of biogenic carbon stored in the built environment.

Construction material and building technology manufacturers

- Develop a road-map to achieve net-zero GHG emissions in the manufacturing and end-of-life treatment of construction materials and building technologies by 2035.
- Create and publish environmental LCA for one's products and organization; utilize EPDs or other established methods to document and provide information and data.
- Optimize manufacturing process, including supply chains by introducing take-back systems, increasing the share of recycled raw materials, increasing the material and energy efficiency, and generally fostering circularity and further reducing the environmental, resource and GHG footprints of one's organization and products.

- Enhance manufacturing processes and supply chains by implementing take-back systems, increasing the use of recycled materials, improving material and energy efficiency, promoting circularity, and reducing environmental, resource, and GHG footprints of one's organization and products.
- Invest directly in negative emission technologies instead of relying on purchasing CO_2 emission certificates to offset residual fossil CO2 emissions.
- Engage with suppliers and ask them to reduce their GHG emissions to net-zero or change to suppliers with lower GHG emissions and more ambitious reduction targets; give preference to suppliers that also have lower environmental impacts and resource consumption.
- Adhere to international standards, utilize an acknowledged and transparent LCA database for accurate assessments, and report in accordance with the principles of a 'true and fair view'.

Construction companies

- Reduce GHG emissions, environmental impacts and resource consumption caused by construction processes for construction and deconstruction.
- Choose or recommend suppliers of construction materials with low GHG emissions, low environmental impacts and low resource consumption.
- Rely on supply transport logistics with low GHG emissions, low environmental impacts and low resource consumption.
- Reduce the amount of waste, and sort and recycle material wasted during construction and deconstruction.

Real estate agents

- Encourage the owners of buildings for sale to share information about their life cycle based GHG emissions, environmental impacts and resource consumption.
- Encourage potential buyers and tenants to ask for information on life cycle based GHG emissions, environmental impacts and resource consumption caused by the buildings under examination.
- **Report on life cycle based GHG emissions, environmental impacts and resource consumption caused by the buildings one offers.**

Users and tenants

- Question the need for a rental in terms of size, level of comfort and equipment.
- **Use life cycle based GHG emissions, environmental impacts and resource consumption as key criteria when selecting a rental.**

- Use energy and water economically and use the rental and its equipment mindfully by, e.g. following cleaning and maintenance instructions.
- Choose energy carriers and products with low GHG emissions, low environmental impacts and low resource consumption.

A more detailed outlook on future developments and the necessary measures to prepare the construction and construction technology sector for the challenges of the future can be found in the construction technology report. It is a guide for decision makers, researchers, companies and interest groups to jointly develop innovative solutions and sustainably drive innovation in construction [279].

Regarding research and development, the IEA currently takes further important steps with IEA EBC Annex 89. The annex aims to support the transition of the building and property sectors towards achieving net-zero whole life carbon outcomes. This will be achieved through several key initiatives, including the development of guidelines for setting whole-life carbon targets, the identification of carbon reduction pathways, and assessment frameworks aligned with the goals of the Paris Agreement. The annex also assesses the tools available to stakeholders for decision making and explores the conditions for the practical adoption of context-based solutions. In addition, multistakeholder engagement is prioritized to ensure effective knowledge sharing and widespread implementation of Annex 89 outcomes [280].

5.5 Conclusions

Rising GHG emissions continue to drive climate change and are increasingly becoming a significant global problem. To limit global warming to less than 1.5 degree Celsius by 2050, the IPCC report estimated that a global carbon budget of approximately 400 billion tons of CO_2 remains. According to the UN Environment Programme, the construction industry is the largest contributor to this drastic development, accounting for 37 percent of total global GHG emissions.

Therefore, the procurement guidelines for buildings are increasingly pushing for awarding contracts based on LCC models that take into account environmental impacts. Recent developments in the EPBD also increasingly emphasize the need to consider life-cycle emissions. These assessments of environmental and economic building performance over the entire life cycle of a building can be performed using the LCA and LCC methods. Although standards exist for applying these two methods in the building sector, they are not applied during the procurement process, i.e. in tendering and awarding.

The developed LCA-based bonus/malus system represents a cost model for the procurement process for buildings, which monetises building-related environmental impacts, i.e. embodied emissions and operational emissions, and considers them in the life cycle costs. The cost model is based on a bonus/malus system, which favours building variants with better environmental performance and disadvantages building variants with worse environmental performance. The monetarization of the environmental indicators is carried out using carbon pricing instruments, with which the amount of the bonus and the malus, and thus the weighting of the environmental performance within the award decision are determined. The application of this cost model promotes LCA-optimized planning alternatives and reduces GHG emissions from the building sector.

For practical application of the developed cost model, minor adjustments are necessary, especially in the tender documents, in contrast to the conventional building procurement process. This includes, on the one hand, the provision of all necessary calculation bases for the implementation of the LCA and LCC and the explanation of the calculation algorithm of the GHG emissions bonus/malus. On the other hand, the cost model as an award criterion and GHG emissions limit values as an exclusion criterion are to be defined within the framework of the award.

The application of the LCA-based bonus/malus system during the validation shows that, depending on the building type, a reduction potential of GHG emissions of up to 38 percent is available.

To plan and construct buildings from a holistic sustainability point of view, it is important not to neglect the effects of an LCA-optimized planning process on other sustainability aspects. For this purpose, a simplified planning support tool, the hierarchical reference-based know-why model, supports the implementation of a systemic planning process by identifying synergies and trade-offs of project goals at an early planning stage. The systemic planning model is based on a systems thinking approach, i.e. the know-why method, and the building certification system of DGNB. With the hierarchical reference-based know-why model, once a reference model has been created based on the objectives of the organization, i.e. planning entire buildings, planning building elements or developing individual materials, various planning variants can be implemented in a very short time in the form of alternatives. Furthermore, the model can be easily and quickly extended to generate a data pool of alternatives.

The application of the hierarchical reference-based know-why model showed that advantages and disadvantages of a planning variant can be highlighted in comparison to the defined reference alternative. Therefore, the application of the hierarchical reference-based know-why model supports the early detection of effects on individual targets and thus reduces the probability of missing quality, cost and schedule targets.

In conclusion, the results and impacts of this doctoral thesis are of importance for the further reduction of the GHG emissions of buildings and thus for the decarbonization of the building sector. The combination of the two developed models highlights the effects of an environmental building procurement process for involved decision makers. The visualization of synergies and trade-offs of an LCA-optimized planning process provides added value for not only planners but for policy makers, legislators and awarding authorities.

Finally, after the introduction and application of the LCA-based bonus/malus system, GHG emission monitoring must be carried out, and a consistent data recording system must be established for Austria. GHG emissions monitoring can be implemented, for example, during the building submission process by requesting and fulfilling predefined GHG emissions thresholds, i.e. similar to checking the compliance with building density. In the future, a consistent data recording system at the municipal and city levels with subsequent transmission of the data to statistical institutes, e.g. Statistics Austria, can show developments in environmental building performance and subsequently support the benchmarking of GHG emissions.

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Appendices

Appendix A - Thesis publications

1. Thesis publication 1: **Implementation of Life Cycle Assessment (LCA) in the Procurement Process of Buildings: A Systematic Literature Review.** Scherz, M., Wieser, A., Passer, A. & Kreiner, H. Published in Sustainability, 2022.
https://doi.org/10.3390/su142416967.

2. Thesis publication 2: **Sustainable procurement for carbon neutrality of buildings: a Life Cycle Assessment (LCA)-based bonus/malus system to consider external cost in the bid price.** Scherz, M., A., Passer, A. & Kreiner, H. Published in Developments in the Built Environment 14, 2023.
https://doi.org/10.1016/j.dibe.2023.100161.

3. Thesis publication 3: **Strategies to improve building environmental and economic performance: An exploratory study on 37 residential building scenarios.** Scherz, M., Hoxha, E., Maierhofer, D., Kreiner, H. & Passer, A. Published in International Journal of Life Cycle Assessment, 2022.
https://doi.org/10.1007/s11367-022-02073-6.

4. Thesis publication 4: **Transition of the procurement process to Paris-compatible buildings: consideration of environmental life cycle costing in tendering and awarding.** Scherz, M., Kreiner, H. Alaux, N., & Passer, A. Published in International Journal of Life Cycle Assessment, 2023.
https://doi.org/10.1007/s11367-023-02153-1.

5. Thesis publication 5: **A Hierarchical Reference-Based Know-Why Model for Design Support of Sustainable Building Envelopes.** Scherz, M., Hoxha, E., Kreiner, H., Passer, A. & Vafadarnikjoo, A. Published in Automation in Construction 139, 2022. https://doi.org/10.1016/j.autcon.2022.104276.

Thesis publication 1

Scherz, M., Wieser, A.A., Passer, A. & Kreiner, H. (2022). **Implementation of Life Cycle Assessment (LCA) in the Procurement Process of Buildings: A Systematic Literature Review.** *Sustainability 14*. https://doi.org/10.3390/su142416967

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Review

Implementation of Life Cycle Assessment (LCA) in the Procurement Process of Buildings: A Systematic Literature Review

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Abstract: The construction industry adds a high share to global CO_2 emissions and, thus, to the global climate crisis. Future buildings need to be planned, constructed, operated, and deconstructed in a lifecycle-oriented manner so that the building stock represents a capital asset for future generations. The greatest leverages for reducing a building's CO_2 emissions lie in the early project phase and subsequently in the tendering and awarding process, which makes early Life Cycle Assessment (LCA) indispensable. In this study, we set a sociological research framework consisting of (i) choosing a research topic, (ii) conducting a literature review, (iii) measuring variables and gathering data, (iv) analyzing data, and (v) drawing a conclusion. Since there are countless studies that apply LCA in the construction sector for environmental assessment, emission reduction, or decision support, we posed the question of whether LCA was also applied in the public building tendering and awarding process. Furthermore, we focused on identifying obstacles to LCA implementation in this early project phase. Therefore, we applied the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines and conducted a Systematic Literature Review (SLR). The results show that numerous articles focused on sustainable tendering or green public procurement in the construction industry; however, the LCA method is scarcely used in the procurement processes (19 articles in the final sample). Based on our findings, the main obstacles to LCA implementation in the procurement process are highlighted in the study. In the future, the mandatory integration of LCA into the procurement process will be crucial to reduce the CO_2 emissions generated by the construction industry and thus contribute to the EU climate target plan to ensure carbon neutrality by 2050.

Keywords: buildings; life cycle assessment (LCA); sustainability assessment; public procurement; tendering; awarding; obstacles detection; sustainable construction

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1. Introduction

In recent years the threats of climate change and remaining carbon budgets have been recognized by progressive efforts such as the Brundtland Report [1], the Rio Declaration [2], the Kyoto Protocol [3], and the 2030 Agenda for Sustainable Development [4]. In addition to these policy documents, the instruments of procurement have evolved in parallel [5]. With public procurement, in particular, the aim is for public actors to be role models and increasingly integrate environmental and social criteria into the procurement processes [6]. Various developments show that environmental and social requirements are increasingly important alongside economic efficiency [7–9].

In 2004 the guidelines of the public procurement environmental and social necessities were included as secondary considerations [10]. The EU directives 2004/17/EC and

2004/18/EC stipulate that contracts may be awarded to bidders based on price if the bidders meet the minimum requirements. In addition, a second alternative is permitted, namely awarding based on the economically most advantageous tender [11,12]. Adopting of these guidelines also formed the starting point for further developments such as green public procurement, sustainable procurement, and green procurement. In addition to regulatory developments, recent legislation has also favored green and social tendering and contracting in public procurement [10].

One of the aims of these two regulations is to reduce the carbon footprint and energy consumption of buildings. In order to meet the requirements of a carbon-neutral environment, the tendering and awarding processes of the construction industry must be further developed for this purpose [13].

Due to the enormous size of the construction sector, it contributes significantly to CO_2 emissions with its high material and energy flows. Consequently, it is a contributor to the ongoing climate crisis, highlighted by the significant share of global CO_2 emissions caused by buildings. Annual global building-related CO_2 emissions totaled 9.0 Gt CO_2 emissions in 2016 and have grown to approximately 10 Gt CO_2 emissions, according to the latest Global Status Report for Buildings and Construction. The share of embodied CO_2 emissions from construction accounted for more than one-third of this total, highlighting the increasingly important role of embodied CO_2 emissions [14]. Furthermore, the annual status reports published by United Nations Environment, the International Energy Agency, and the Global Alliance for Buildings and Construction report that 36 percent of global final energy consumption and 37 percent of energy-related CO_2 emissions can be accounted to buildings and their operations. In addition, the report shows that a further 10 percent of energy-related CO_2 emissions are generated by the sector referred to as the other construction industry [15]. Breaking down the share of embodied CO_2 emissions to the member states of the European Union (EU), CO_2 emissions from material extraction, construction product manufacturing, building construction, and refurbishment are estimated to be around 5–12 percent of the respective national CO_2 emissions [16]. With regard to the environmental impact of buildings, a literature review analyzed the environmental modeling of the building stock and presented corresponding EU policy initiatives [17]. In addition, frameworks already exist to harmonize the definition of the carbon budget of buildings from different perspectives and at different spatial and temporal scales [18]. Hence, future buildings need to be designed, constructed, operated, and deconstructed in a holistic and lifecycle-oriented manner, taking into account systemic interdependencies so that the building stock represents a capital asset for future generations and not a legacy [19,20]. In order to achieve these targets, methodical approaches and tools are already available to support sustainable construction, i.e., to support the implementation of more environmentally friendly construction through the reduction of CO_2 emissions [21,22]. In this context, the Life Cycle Assessment (LCA) method can be used to evaluate the environmental impacts of buildings and, thus, calculate the CO_2 emissions caused during their entire life cycle [23].

The method of LCA and its calculation rules are standardized for general use in the ISO 14040 and ISO 14044 standards [23,24]. In relation to these and other standards, e.g., ISO 9000 series or ISO 14001, which address topics such as quality management or environmental management, a difference can be made between organization-related standards and product-related standards [25]. An overview of these standards and their relations can be found in [26].

In the construction sector, the methodology was pushed forward by the CEN TC350, especially with the EN 15978, in which sustainability for the construction industry and the application of LCA for buildings are defined [27]. In recent years much research has focused on the methodological development of LCA, why the LCA is a widely applied method, especially in the construction industry [28]. In addition to methodological approaches, application at an early design stage of buildings is also under continuous development [22,29–31]. Numerous studies also showed the application of LCA for comparing variants of materials, construction elements, or buildings to evaluate the environmental impacts and to make sustainable decisions based on the results [32–36].

The rapidly growing field of LCA ″n th′ construction industry is reflected in numerous literature studies. Studies examined the application of LCA in the general context of the construction industry [36,37], and specifically the LCA application in the early project or design phase of buildings [38,39]. Further literature studies addressed LCA with a focus on embodied emissions and emphasized its importance in consideration of total emissions [17,40]. In this context, literature studies of LCA application for a wide variety of materials, such as timber, brick, concrete, or insulation materials, are also available [41–44]. Regarding construction materials, other studies went further into detail and investigated the application of LCA on those individual components of these materials using literature studies. These include, among others, the application of LCA to aggregates or cement mortar [45,46]. There are also already literature studies on the application of LCA for individual life cycle phases, such as the refurbishment phase or the end-of-life phase [47,48].

A recent study also analyzed the ″evel′pment of LCA in European policy. The results show that LCA is increasingly mentioned in policy, but the development of new and mandatory requirements related to LCA is still limited [45]. However, it appears that early assessment of the environmental performance of buildings will be mandatory in the future, but the voluntary wide practical application of LCA does not exist yet. Based on this observation, we were interested in determining the current status of LCA application in the building tendering and awarding processes. The first part of this study analyzed the question of whether LCA was applied in the procurement phase of buildings from the perspective of the literature. If LCA was not applied in the procurement phase of buildings, in the second part, we aimed to investigate why it was not applied and what the obstacles to implementation from a practical perspective were.

For this purpose, in this article, the main stages of the sociological research framework, (i) choosing a research topic, (ii) conducting a literature review, (iii) measuring variables and gathering data, (iv) analyzing data, and (v) drawing a conclusion, were applied in this article. The research topic addressed the application of LCA in the building procurement process. To gain better insights into the application of LCA in the tendering and awarding processes of public building projects, this article aimed to present the current state-of-the-art considerations of the LCA method in public procurement. For this purpose, the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines were applied to conduct an SLR. The research included a pre-selection and evaluation of current and qualified literature studies to answer two specific research questions:

(i) "Is LCA applied in the procurement processes of buildings?"
(ii) "What is hindering the implementation of LCA in building procurement processes?"

While a few studies analyze the implementation of LCA in the construction procurement process based on real case studies and court cases [49–51], the novelty of our study lies in the comparison of this topic through a comprehensive literature review. Another uniqueness lies in identifying specific obstacles to LCA implementation that occur directly due to the implementation of LCA in the procurement process.

The following parts of this article are structured as follows. Section 2 discusses the materials and methods used in our research. Section 3 presents the results of the meta-data analysis, followed by the discussion of the findings in Section 4. Finally, the conclusions are drawn and the limitations and future research directions shown in Section 5.

2. Materials and Methods

2.1. Systematic Literature Review

The analysis and illustration of the current state-of-the-art consideration were conducted using a systematic literature review (SLR). The main steps of the SLR are (i) the definition of the research question(s), (ii) the definition of keywords and search strings, (iii) the definition of constraints (databases, search period, language, type of literature), (iv) article exclusion by title, (v) article exclusion by abstract, (vi) article exclusion by full paper and (vii) the analysis of meta-data. The process of the SLR is shown in Figure 1 based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flowchart [52]. Detailed explanations on how to perform the SLR, as well as the included snowball approach, can be found in [53,54]. After completing both the SLR and the snowball approach a final sample was found consisting of 19 articles for in-depth analyses.

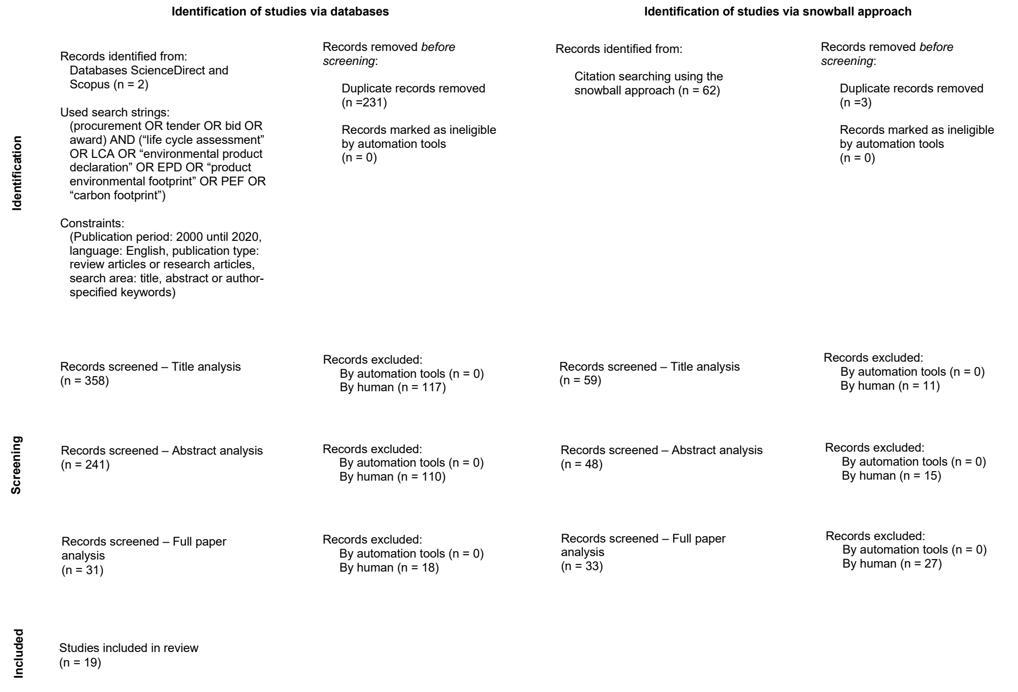

Figure 1. Overview of Systematic Literature Review (SLR) and snowball approach according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guideline.

2.2. Preferred Reporting Items for Systematic Reviews and Meta-Analyses

The PRISMA 2020 Statement is the latest updated version on the guideline for conducting and reporting systematic reviews. The guidance consists of 27 items presented in a checklist and focueses on the introduction, the methods, the results, and the discussion section of a SLR [52,55]. The SLR performed in this article was consistent with the PRISMA 2020 Statement.

2.3. Snowball Approach

Snowballing is an approach within SLRs and can be divided into forward snowballing and backward snowballing. Both approaches work with cited references. While forward snowballing identifies new papers that reference papers already included in the final sample, backward snowballing examines the references of articles in the final sample and, thus, adds more relevant articles to the final sample [53].

2.4. Final Sample Identification Process

Based on the two defined research questions, the keywords procurement, tender, bid, award, life cycle assessment, LCA, environmental product declaration, EPD, product environmental footprint, PEF, and carbon footprint were defined for conducting the SLR.

It must be mentioned that the focus of the article was to analyze the current application of LCA in the procurement process of buildings and identify obstacles to implementation. However, keywords such as environmental product declaration, product environmental footprint, and carbon footprint were also used since LCA can also be closely associated with these terms and was a prerequisite for the generation of EPDs or the calculation of carbon footprints. Moreover, it aimed to enlarge the data pool from the beginning to avoid excluding any articles.

These keywords were combined in the search string (procurement OR tender OR bid OR award AND "life cycle assessment" OR LCA OR "environmental product declaration" OR EPD OR "product environmental footprint" OR PEF OR "carbon footprint") using the Boolean operations "OR" and "AND". The search for relevant articles was performed in two databases, ScienceDirect and Scopus. In the search, certain constraints were applied to limit the search results to relevant target articles. The first constraint was made based on the search period. The SLR included literature from the years 2000 to 2020. The second constraint was the language of the included literature, which was set to English only. The third constraint was the type of literature, which was set to review articles and research articles. The last constraint concerned the search area of the search string in the two databases. The search string was only applied to title, abstract, or author-specified keywords.

After applying the search string and the defined constraints in both databases, 569 articles were found. After excluding duplicates, the search comprised 358 articles. After that, the identified articles were further reduced based on the relevance of the title. This process was performed as a double-check, i.e., two persons each performed this step to increase the quality of the exclusion process. After this process step, 241 articles remained, which were further reduced in the next step based on the relevance of the abstract. This process step also took place as a double-check. This exclusion process resulted in 31 articles for the final full paper analysis. Detailed screening of the 31 articles revealed that 13 articles were relevant in answering the research questions and were thus included in the final sample.

After conducting the SLR, the snowball approach was used as an additional iterative step. In the case of the snowball approach, the reference list was screened from the 31 articles analyzed, and further relevant articles were identified based on references. This first step of the snowball approach resulted in an additional 62 articles, which were reduced to 59 articles after removing duplicates. As with the SLR, the exclusion of articles by the relevance of the title (48 articles left) and abstract (33 articles left) was based on the double-check principle. All the exclusion steps were performed by humans, and no automation tools were used. The detailed full paper analysis of the 33 articles resulted in 6 relevant articles that were included in the final sample. In the end, the final sample for the meta-data analysis consisted of 19 articles.

3. Obstacles to the Implementation of LCA in the Procurement Process of Buildings

Derived from the identified literature based on the defined keywords and constraints during the SLR, a final sample of 19 articles resulted. From this, it can be deduced that the method of LCA is scarcely applied in the procurement process of buildings. Obstacles to LCA implementation in the procurement process were various and could be categorized according to different aspects. To answer the question of obstacles to LCA implementation, five obstacle classifications were defined: (i) methodological obstacles,

(ii) organizational obstacles, (iii) legal obstacles, (iv) political obstacles, and (v) economic obstacles.

Methodological obstacles refer to the LCA method itself and can also be described as general obstacles that do not occur directly in the implementation of the construction procurement processes. In addition to these general obstacles, the other obstacle classifications represent specific obstacles that occur in implementing LCA in the building procurement process. Organizational obstacles are individual obstacles that can occur to varying degrees in individual companies, and these obstacles are particularly dependent on the size of the organizations. Legal and political obstacles are mainly based on a lack of legal requirements and initiative to support alternative building procurement processes. However, it should be noted that methodological, legal, and political obstacles, in particular, are interdependent. If there are too many methodological obstacles, it is difficult for policymakers and legislators to take the next steps toward mandatory LCA implementation in the tendering and awarding process. Economic obstacles are those that prevent LCA implementation primarily because of the additional cost involved.

Figure 2 shows the occurrence of the addressed categories in the final sample.

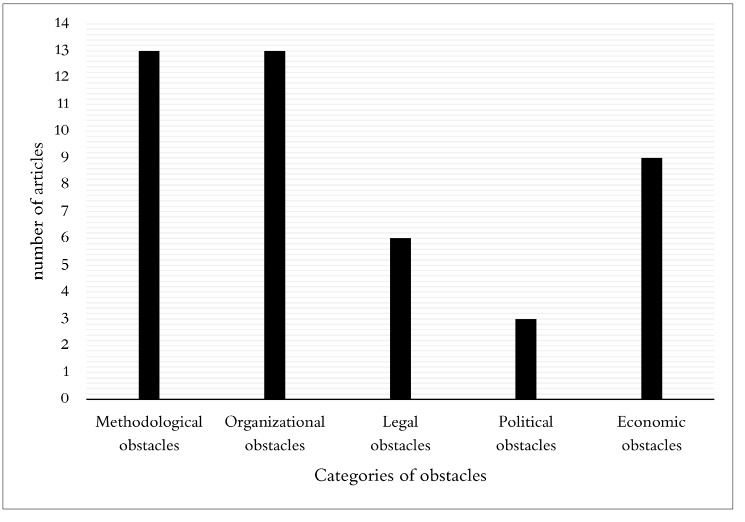

Figure 2. Categories of obstacles to implementing LCA in the procurement process of buildings.

3.1. Methodological Obstacles

An identified obstacle on the methodological level was the lack of comparability for the different LCA tools and results in the LCA process, e.g., allocation or impact categories, for tender requirements [56–59]. In this context, the different ranking results of variants for different indicators were also highlighted as obstacles [60]. Furthermore, in addition to the lack of practical and operational tools, the high complexity of the LCA process made the implementation of LCA in the tendering and awarding procedure difficult [59,61–67]. Moreover, a lack of information, e.g., missing guidelines, handbooks, or toolkits, was mentioned as a problem for LCA implementation [59,61,65]. Process-based obstacles and problems in the procurement procedure context included different challenges to be tackled in the award criteria, meaning that environmental preferences were formulated in a way that is too unspecific or they were difficult to measure in the first place [67,68]. On top of this, the assessment criteria and the award criteria did not always correspond to the importance of the environmental issue [68]. Additionally, the distinct use of tender processes or award criteria could also be an issue, as well as the tendency to use environmental criteria more often with higher project budgets or on a national level [61,68]. Lastly, the lack of methods that enabled comparisons, quality control, and monitoring was mentioned [67]. In terms of data quality, the availability of data and data uncertainty were also identified as methodological obstacles [60,67]. Table 1 provides an overview of the identified methodological obstacles. The applied methodological approaches of the research articles (italic), as well as the obstacles, are mentioned.

Table 1. Methodological obstacles to the LCA implementation in the procurement process of buildings.

Methodological Obstacles	Reference
Review of PEF guide and EPDs *Comparison between the PEF guide and the EPD requirements* → PEF and EPDs are not comparable in terms of results → PEF and EPDs in their current form cannot be alternatively used as tools supporting GPP tender requirement	[56]
Review of to-date EPD programs for pavement materials *Discussion about stakeholders' perspectives on the current EPD program with material manufacturers, public government agencies, and LCA consultants* *Use of EPDs in GPP to ensure the environmental improvement of materials and pavements* → EPDs aggregate a LCI into a handful of mid-point indicators, which can undermine the details of the supply chain	[57]
Discussion with stakeholders (owner/client, designer, and contractor) about EPD implementation *Application of EPDs during the design and construction stage using an office building as case study* → Lack of result comparability of different LCA tools	[58]
LCA/TOPSIS method is applied to public procurement of urban furniture *Simplified LCA methodology combined with TOPSIS method for assessing award criteria* → Lack of guidelines/handbooks for LCA implementation → No monetization of LCA results	[59]
LCA is applied to road bridges to push LCA implementation in procurement *Comprehensive LCA framework for road bridge procurement* → Different ranking results for different indicators → Uncertainties in data	[60]
Content analysis of the documents obtained from calls for tenders *Comparison of environmental criteria in tenders* → Complex LCA process → Missing guidelines or toolkits → Distinct use of tender processes or criteria → Use of environmental criteria with higher project budgets	[61]
Semi-structured interviews about current practices and obstacles to environmental requirements in construction *Survey about the existence of municipal policies dealing with environmental issues* → Lack of data quality about material inventories → Environmental performance requirements are too complex	[62]

→ Lack of guidance and standardization at national level	
LCA for design selection and decision-making during material procurement of asphalt mixtures *Analytical approach to identify equivalence intervals that are applicable during material procurement decision-making* → High complexity of the LCA process → Lack of uncertainty analysis within LCA	[63]
Structured interviews on the assessment of environmental aspects and the review of environmental requirements *Survey about including environmental requirements in procurement documents* → Complexity of LCA analysis → Lack of evaluation of operating energy → Lack of LCCA integration → Lack of assessment models	[64]
Assessment of the determinants and drawbacks of green procurement adoption → Lack of guidelines and tools to support GPP	[65]
LCA is applied to wood windows to support procurement criteria definition → Lack of practical and operational tools	[66]
Literature review of obstacles and drivers for sustainable buildings *Interviews about obstacles and drivers for sustainable buildings* *Case studies on improving the sustainable building process and the impacts and benefits of sustainable buildings* → No methods that enable comparisons, quality control, and monitoring → No methods to verify the compliance of subcontract's work with the sustainability requirements → Lack of available information → Design documents do not show adequate performance and capacity requirements for the products	[67]
Interview series to achieve insights into application of environmental preferences in construction projects *Survey about the application of environmental preferences in the procurement of construction contracts* → Environmental criteria are weighted less heavily → Environmental criteria have therefore no influence on the results of the evaluation	[68]

Within the methodological obstacles, the lack of standardization at a national level was mentioned as an implementation obstacle. However, as far as the LCA method is concerned, the international standards ISO 14040 and ISO 14044 define the calculation principles of LCA [23,24]. In addition, there is even a standard for the application of LCA to calculate the environmental performance of buildings [27]. The application of these standards and, therefore, the application of LCA in the construction industry is already far-reaching and, therefore, cannot be an obstacle to implementation. In addition, the lack of guidelines and handbooks was mentioned a few times as a barrier to implementation. In terms of LCA implementation in general and specifically for the calculation of embodied emissions, guidelines for designers, policymakers, and manufacturers have already been developed [69–72]. Regarding the implementation of LCA within the building's procurement process, these guidelines and handbooks are lacking, as the assessment of the environmental performance of buildings in the course of tendering and awarding is uncharted territory and is still scarcely applied in practice. In this context, new approaches are currently being developed in the research project "Paris Buildings" [73]. For the calculation of the economic performance of buildings, i.e., life cycle costing (LCC), there are already guidelines in Austria for the implementation of LCC in the building procurement process [74,75]. Based on these guidelines, a guidance document for the implementation of LCA in the building procurement process could also be oriented.

Regarding the LCA process, its complexity was highlighted as a problem for application in the procurement process. Closely related to this, the problems of varnishing of the data and also data quality due to underlying uncertainties are also emphasized. To make the complexity manageable, the know-how on all sides of the project participants must be increased. Nevertheless, sustainability assessment experts are recommended (especially in the initial application phase) in order to support the mandatory implementation of LCA in the tendering and awarding of buildings. By consolidating these experts, the valid examination of the submitted offers is guaranteed by complete, transparent, and consistent LCA. Although numerous LCA databases such as Ecoinvent, ELCD database 3.1, GaBi Database, and Ökobaudat are available, new/specific data sets will always be needed due to the uniqueness of buildings [76]. Implemented sustainability experts can also close the practical gap concerning "data-lack," since new project-specific data sets can be modeled by themselves. This is crucial in terms of time expenditure during a mostly strong limited planning phase.

In the uncertainty context, this was equal for all bidders, i.e., all submitted bids, if external and independent experts were involved. Regarding the lack of data in relation to the operating energy that was mentioned, it could be referred to the national obligatory energy standards [77]. How the effects of different energetic standards influenced the results of the LCA was investigated in [78]. The mentioned lack of assessment models can be solved only partially in the future. Due to the fact that each building is unique, the development of a generally applicable assessment model/tool is not reasonable. In this context, however, there were already several approaches to automatically link LCA databases with Building Information Models (BIM) [79,80]. LCA software, such as SimaPro, Gabi, Umberto, and openLCA [81,82], has been available for decades but is often associated with high acquisition costs.

Regarding the LCA results, the problem here was that different results were obtained with respect to the best-case scenarios depending on the considered environmental indicators, i.e., for the environmental indicator of Global Warming Potential, a different scenario was better than for the environmental indicator of Eutrophication Potential. If all environmental indicators are taken into account, this problem can only be solved with a defined weighting of the different indicators and their normalization to one value [83]. However, the first important step was the consideration of environmental indicators that address the most vulnerable areas of the planetary boundaries [84,85].

In the context of considering environmental indicators in the tendering and awarding process, the obstacle to the lack of monetization opportunities for environmental indicators was mentioned. However, recent literature has already provided conversion values for many environmental indicators [86–89]. Sensible values of these conversion factors to achieve meaningful environmental optimization (based on so-called "environmental break-even" points) are currently being analyzed within the research project "Paris Buildings" [73].

3.2. Organizational Obstacles

In terms of organizational obstacles, one challenge was missing environmental knowledge within existing organizations and the lack or limited knowledge connected with LCA and other green public procurement (GPP) tools [61,62,90,91]. In this context, the insufficient knowledge to develop clear targets and mitigating strategies and the problem that contractors were not able to explain sustainability criteria to subcontractors were highlighted as obstacles [62,65,67]. In addition, there was a lack of common goals because not all stakeholders shared the same conviction for addressing environmental issues [92]. A further challenge occurred if there were no clear responsibilities assigned to the LCA [62]. The problem with LCA implementation was often that green alternatives like supply chains or services were unavailable [65,90,92,93]. Another challenge was the fear of high- and time-consuming bureaucracy and project delays [68]. In addition, a lack of access to appropriate data was a significant challenge to the application of LCA [62,64,66]. Finally, the lack of time to compare alternatives, as well as the lack of training for employees, were described as organizational obstacles [58,65,67,92]. Table 2 provides an overview of the identified organizational obstacles.

Table 2. Organizational obstacles to LCA implementation in the procurement process of buildings.

Organizational Obstacles	Reference
Discussion with stakeholders (owner/client, designer, and contractor) about EPD implementation *Application of EPDs during the design and construction stage using an office building as case study* → Lack of time to apply an LCA	[58]
Content analysis of the documents obtained from calls for tenders *Comparison of environmental criteria in tenders* → Missing knowledge and skill regarding LCA and other GPP tools	[61]
Semi-structured interviews about current practices and obstacles to environmental requirements in construction *Survey about the existence of municipal policies dealing with environmental issues* → Lack of skills related to LCA tools and methods	[62]
Assessment of environmental impacts of two different hot mix asphalt (HMA) materials to provide evaluation parameter in public bids → Lack of comprehensive approach for application to different civil works → Lack of green alternatives	[93]
Structured interviews on the assessment of environmental aspects and the review of environmental requirements *Survey about including environmental requirements in procurement documents* → Lack of knowledge of environmental strategies → Lack of input data → Lack of expertise in assessing environmental impacts	[64]
Assessment of the determinants and drawbacks of green procurement adoption → Lack of training for employees → Difficulties in the preparation of tenders and purchases → Lack of information about environmental impacts	[65]
LCA is applied to wood windows to support procurement criteria definition → Lack of appropriate data	[66]
Literature review of obstacles and drivers for sustainable buildings *Interviews about obstacles and drivers for sustainable buildings* *Case studies on improving the sustainable building process and the impacts and benefits of sustainable buildings* → Insufficient knowledge to develop clear targets and mitigating strategies	[67]

→ Contractors are not able to explain the sustainability criteria for subcontractors → Client lacks an actor who supports him in setting targets for sustainability requirements → No resources to supervise the realization of sustainability requirements → Not enough time to compare alternatives	
Interview series to achieve insights into application of environmental preferences in construction projects *Survey about the application of environmental preferences in the procurement of construction contracts* → Fear of high- and time-consuming bureaucracy → Insufficient knowledge → Fear of project delays	[68]
Assessing the environmental impact of road works to promote green procurement using multi-criteria analysis → Lack of knowledge connected with LCA → Technical and organizational difficulties during the management of green tenders	[90]
LCA is applied for two products to support procurement decision → Additional time effort for LCA application → Lack of know-how in the field of LCA	[91]
Semi-structured interviews to develop a framework for a carbon emission encompassed tender *Framework for a carbon emission encompassed tender* → Lack of a common goal because all stakeholders must be convinced → Missing know-how in implementing low carbon measures for small firms → Project constraints in terms of design and specifications	[92]
Development of the Thai National LCI Database → Lack of stakeholder awareness → Lack of LCA expertise	[94]

Among the organizational obstacles, the additional time required to conduct LCAs in the procurement process was cited as an implementation barrier. This obstacle cannot be completely eliminated, as additional tasks usually require additional time. However, the complex LCA process and, thus, the time required can be significantly reduced through the generation of know-how and accumulated project experience, and, as mentioned above, the implementation of sustainability experts can close this gap. Nevertheless, it must be mentioned that the main hurdle for most organizations was still the real and substantial implementation of sustainability concepts [95]. In addition to the lack of time to conduct LCA, the lack of time relating to designing and comparing more environmentally friendly alternatives was also mentioned as an obstacle to implementation. Overcoming these obstacles requires a transformation of the design process [96] and more innovative remuneration models. For example, in Austria, there was already a fee structure in the form of scheduled services and fees for architects and engineers (HOAI), which defined special services in addition to standard services.

Early LCA implementation in the tendering and awarding process of buildings also failed due to the lack of know-how within the organizations involved. This problem was based on the fact that it is currently not common practice to implement LCA in the procurement process of buildings and that organizations do not offer their employees either any training or further education opportunities in this subject area. In this context, however, it must be mentioned that this transformation of the design process towards sustainable procurement of buildings is a further step similar to the application of BIM. BIM is already state-of-the-art in many planning offices and is constantly being further developed. In BIM, there are, in addition to the 3D building models, also possibilities to consider 4D (cost), 5D (time), and 6D (sustainability aspects) models [97–99].

In addition to the lack of time and know-how, missing access to data for the organization was also mentioned as an implementation obstacle. In this regard, however, it must be emphasized that there are freely accessible databases such as Ökobaudat. On the other hand, several databases are not freely accessible and must be purchased through high license fees. In this context, harmonizing all LCA databases would be an important step for a future, environmentally friendlier construction industry.

An obstacle to implementation on the part of awarding authorities was the lack of awareness and understanding to explain clear targets related to the implementation of sustainability aspects. Recently, there has been an increasing awareness of sustainable building procurement. In Austria, for example, the city of Graz already uses a developed form sheet for climate change and sustainability on a voluntary basis in the course of architectural competitions [100]. Other approaches, such as the use of a systemic design process or a maturity assessment, can further raise awareness and contribute to the reduction of CO_2 emissions in the construction industry [21,22].

3.3. Legal Obstacles

The problems in the area of legal obstacles lay in missing compulsory environmental requirements by law, such as the use of LCA in tender processes [61,90]. The lack of regulations for public tenders was mentioned in this context [101]. Furthermore, attention was drawn to the lack of clarity in the law regarding environmental requirements [62]. These two mentioned obstacles were emphasized by the lack of consistent format in terms of legal requirements [91]. Moreover, the institutionalization of green procurement is slow due to the absence of extensive and well-defined rules for incorporating environmental criteria into procurement procedures and awarding contracts for goods and services [65]. Table 3 provides an overview of the identified legal obstacles.

Table 3. Legal obstacles to LCA implementation in the procurement process of buildings.

Legal Obstacles	Reference
Content analysis of the documents obtained from calls for tenders *Comparison of environmental criteria in tenders* → Missing compulsory environmental requirements for LCA implementation	[61]
Semi-structured interviews on the subjects of current practices and obstacles to environmental requirements in construction *Survey on the subject of the existence of municipal policies dealing with environmental issues* → Law is unclear regarding environmental requirements	[62]
Assessment of the determinants and drawbacks of green procurement adoption → Absence of extensive and well-defined rules for incorporating environmental criteria into procurement procedures and the awarding of contracts for goods and services	[65]
Assessing the environmental impact of road works to promote green procurement using multi-criteria analysis → Missing compulsory environmental requirements	[90]
LCA is applied for two products to support procurement decision → Lack of consistent format in terms of legal requirements	[91]
Review of EPDs	[101]

Comparison of EPDs and NAPs → No regulations for public tenders	

In the context of the legal obstacles, the unclear legislative regulations regarding environmental requirements were highlighted as an implementation barrier to early LCA application. With reference to these findings, it is worth mentioning that the procurement directives, i.e., EU directives 2004/17/EC and 2004/18/EC, have evolved towards greener procurement in recent years. However, the contents defined leave a relatively high scope of action in terms of (practical) implementation [11,12]. Especially the application of LCA is still on a voluntary basis. Furthermore, it was criticized that there are no regulations for public tenders. However, in this context, there are approaches for green public procurement of office buildings to integrate LCA into the procurement process [102].

3.4. Political Obstacles

In the context of the obstacles under policy aspects, municipal authorities did not use the right to set sustainability requirements as award criteria. Further obstacles mentioned in the literature were the lack of a comprehensive strategy for public procurement and the lack of governance of regulation, regardless of its nature, which could be either performance-based or prescriptive [67]. Moreover, it was mentioned that more than just the indicator of global warming potential (GWP) should be considered as environmental criteria [93]. Lastly, missing supporting initiatives for the implementation of LCA in the procurement process were highlighted as a problem [94]. Table 4 provides an overview of the identified political obstacles.

Table 4. Political obstacles to LCA implementation in the procurement process of buildings.

Political Obstacles	Reference
Literature review of obstacles and drivers for sustainable buildings *Interviews about obstacles and drivers for sustainable buildings* *Case studies on improving the sustainable building process and the impacts and benefits of sustainable buildings* → Municipal authorities do not use the right to set sustainability requirements as award criteria	[67]
Assessment of environmental impacts of two different hot mix asphalt (HMA) materials to provide evaluation parameter in public bids → Lack of a comprehensive strategy for public procurement → More than GWP should be considered as environmental criteria	[93]
Development of the Thai National LCI Database → No supporting initiatives	[94]

Among the political obstacles to implementation, the lack of comprehensive strategies for public procurement was mentioned. Clear strategies for implementing LCA in the tendering and awarding process of buildings do not exist to a sufficient extent. However, sustainability strategies, in general, are increasingly being pushed forward. In this regard, the 17 Sustainable Development Goals (SDGs) within the framework of the 2030 Agenda must be mentioned [4]. Within these goals, SDG 11 "Sustainable Cities and Communities" should be highlighted, which, among other issues, promotes more environmentally friendly construction. As part of the UniNEtZ research project, options for action were developed for the Austrian federal government to achieve the SDGs, which, among other matters, also propose and explain the implementation of LCA in the procurement process of buildings [103]. Another policy instrument that has already been implemented in the context of CO_2 emissions reduction is the implementation of CO_2 taxes.

Another obstacle to implementation mentioned was the lack of supporting initiatives. An organization, e.g., a publicly financed consulting office, could be established here, at least for public buildings, which would provide support in adapting the tender documents, as well as sustainability experts who would carry out the transparent evaluation of the bids. A public consulting office can also overcome the implementation obstacle of municipalities not using the right to set sustainability requirements as award criteria.

3.5. Economic Obstacles

The main factors hindering LCA or GPP implementation on the economic level were resource constraints, i.e., intensive resources for data management, lack of time, and the enormous time requirement for applying an LCA tool [57]. Next to the lack of time, the increased costs were mentioned in the literature. In this context, the establishment of standardized procedures was described as long, which led to a high initial cost [62,64,91]. Staff training for this process also brought financial burdens [62]. In detail, the problems lay in the shortage of resources for supporting GPP, the fear of even further increased costs, and the fact that developers may not be willing to bear these additional costs [58,65,68,92]. An obstacle was also identified as the lack of funding support for LCA implementation, e.g., for LCI development [94]. Table 5 provides an overview of the identified economic obstacles.

Table 5. Economic obstacles to LCA implementation in the procurement process of buildings.

Economic Obstacles	Reference
Review of up to-date EPD programs for pavement materials *Discussion about stakeholders' perspectives on the current EPD program with material manufacturers, public government agencies, and LCA consultants* *Use of EPDs in GPP to ensure the environmental improvement of materials and pavements* → Collecting EPDs to establish benchmarks is resource intensive and requires advanced data management	[57]
Discussion with stakeholders (owner/client, designer, and contractor) about EPD implementation *Application of EPDs during the design and construction stage using an office building as case study* → Additional cost for LCA application → Consideration of environmental products can lead to additional cost regarding transport	[58]
Semi-structured interviews about current practices and obstacles to environmental requirements in construction *Survey about the existence of municipal policies dealing with environmental issues* → Establishing standardized procedures is time consuming and costly → Process of training staff is time consuming and costly	[62]
Structured interviews on the assessment of environmental aspects and the review of environmental requirements *Survey about including environmental requirements in procurement documents* → High initial cost	[64]

Assessment of the determinants and drawbacks of green procurement adoption → Lack of money to support GPP	[65]
Interview series to achieve insights into application of environmental preferences in construction projects *Survey about the application of environmental preferences in the procurement of construction contracts* → Fear of increased cost	[68]
LCA is applied for two products to support procurement decision → Additional cost for LCA application	[91]
Semi-structured interviews to develop a framework for a carbon emission encompassed tender *Framework for a carbon emission encompassed tender* → Developers may not be willing to bear additional cost	[92]
Development of the Thai National LCI Database → No funding supports for LCI development	[94]

From an economic persepective, the obstacles to LCA implementation in the tendering and awarding phase were very clear. The additional costs were highlighted as a barrier to implementation. These additional costs were seen in the broader sense as environmental damage costs. The construction of new buildings increases CO_2 emissions and, thus, has a negative impact on our environment. In general terms, there are two different theoretical approaches to monetizing these external environmental damages, the damage cost approach and the abatement cost approach. In the abatement cost approach, the focus is not on the cost of the damage caused but on the cost of abatement. The cost incurred by these measures, i.e., the additional cost for LCA implementation, are referred to as abatement costs [104]. In general, there are already standards in the EU for the calculation of environmental damage costs [105,106]. However, in addition to the calculation principles of the LCA, a monetization value such as the CO_2 price must also be specified in the tender documents.

Another obstacle to implementation, which specifies the additional cost mentioned above, was the additional cost required to establish standardized procedures, which companies were unwilling to pay. Training costs for the staff to build up LCA expertise also fell under this additional cost. These barriers were further compounded by the fact that there are no funding supports for the implementation of early LCA. The establishment of a so-called "(public) climate fund," which also addresses the pre- and post-procurement phases, could reduce these additional costs during the initial implementation of more environmentally friendly building projects.

4. Discussion

The increase in the number of new buildings due to rising urbanization increases the share of CO_2 emissions caused by the construction industry. Current tendering and awarding practices for buildings are mainly focused on minimizing cost and almost completely disregard environmental criteria when awarding contracts. However, standards and tools, like LCA, for assessing the environmental performance of buildings are already available. There are only a few real case examples of implementing LCA in building procurement processes [50]. The determination of obstacles to applying LCA at this early project stage is still ambiguous. Identifying these obstacles will help project stakeholders avoid these hurdles in advance and thereby reduce CO_2 emissions emitted by the construction industries through more environmentally friendly tendering and awarding procedures.

For the state-of-the-art identification of LCA implementation in the procurement process of buildings, and thus for the determination of obstacles, an SLR was conducted.

The SLR results show that the implementation of LCA in the procurement process of the construction industry is scarcey addressed in the scientific literature. This is the case despite the fact that the concept of procurement is constantly developing in the direction of environmental procurement in European directives and national action plans with terms such as green procurement, sustainable procurement, and environmental procurement. The identified obstacles to overcome were summarized within the following five categories (i) methodological obstacles, (ii) organizational obstacles, (iii) legal obstacles, (iv) political obstacles, and (v) economic obstacles.

The classified obstacles were divided into general and specific obstacles. While methodological obstacles occurred due to the LCA method itself and are not directly related to the tendering and awarding process of buildings, specific obstacles, i.e., organizational, legal, political, and economic obstacles, occurred directly due to LCA implementation in the building procurement process.

At the methodological level, an approach to implementing LCA in procurement was to establish a well-accepted methodological framework and transparency regarding the use of methods and data. Additionally, the need to develop LCA tools for the whole building was expressed in the literature. For better decisions, and as well in combination with different methods, LCAs should be used as a decision-making tool to judge various alternatives and their environmental implications. For example, the method of comparative LCAs or EPDs was used to push alternatives with lower environmental impacts [28]. The application of environmental criteria could be integrated into the tendering of building services and construction contracts. Another approach was to implement criteria in the preliminary architectural competition [100].

At the organizational level, managers and leaders are crucial when it comes to incorporating environmental preferences into policy documents. Another starting point for improving the situation for LCA in tender documents is the importance of communication and coordination between stakeholders. Improving skills and knowledge transfer, as well as strengthening capacity regarding LCA and awareness of the topic in general, played an important role. Especially education and training regarding the topic of LCA and environmental issues of relevant stakeholders were important. Another important prerequisite for conducting LCA is high-quality LCA data that is scientifically sound, consistent, reliable, and comparable.

At the legal level, appropriate guidelines, tools, and manuals are needed to provide the necessary knowledge for LCA and its mandatory implementation. In addition, standardized methods for the assessment of construction products would be beneficial and should be regulated at the legal level. In this context, the lack of mandatory anchoring of LCA in the tendering and awarding process, as well as award decisions based on financial aspects, i.e., the principle of the lowest bidder, were highlighted.

In the political context, both the lack of regulatory control, which could be either performance-based or prescriptive, and the lack of a comprehensive environmental strategy for public projects were described as obstacles. Moreover, the leadership of government and professional institutions must be introduced to green procurement if greener procurement is desired.

At the economic level, an approach to financing the additional effort involved in conducting an LCA needs to be developed. Instruments such as environmental management control in the pre-procurement and post-procurement phases or climate funds could help here. Furthermore, within the economic category, additional costs due to increased time and effort were mentioned.

In summary, most of the obstacles were found in the methodological and organizational categories. The reasons for not applying LCA were the lack of comparability between different LCA tools, the high complexity of the LCA process, and the lack of information, e.g., user-friendly guidelines, handbooks, or toolkits. These problems were amplified by the missing environmental knowledge within existing organizations and the lack of limited knowledge connected with LCAs. In addition, in most organizations, there are fewer green alternatives and often no access to the necessary data to perform an LCA. It can be argued that most of the obstacles in the three categories of methodological aspects, organizational aspects, and economic aspects can be removed more quickly if appropriate measures are taken at the political and legal levels. However, it must be mentioned that the classified obstacles occur occurred at different levels and are, therefore, not directly comparable. Furthermore, these levels of obstacles were also interrelated and therefore influenced each other. In particular, methodological obstacles influence political and legal obstacles and vice versa. If there are too many methodological obstacles, it is difficult for policymakers and legislators to take the next steps toward mandatory LCA implementation in the building procurement processes.

Not to be neglected in this context is the assessment of the cost efficiency of buildings. In the EU Directives, the concept of life cycle costing (LCC) was mentioned in Article 68. It stated that an *"LCC may also include the costs of externalities (such as greenhouse gas emissions)."* This requires the use of LCA in the procurement process to calculate GHG emissions. Life cycle costing remains optional, but according to Article 68(3), life cycle costing became mandatory when there was a common EU methodology [107].

The limitations of the study lay in the selection and number of databases. Over the course of the SLR, the databases ScienceDirect and Scopus were used. Further limitations concern the constraints that were made within the SLR. The search period was limited to the years 2000 to 2020. Regarding the defined keywords, the performed SLR only included articles that fell under the defined keywords and the search strings produced by combination with the Boolean operators. Other synonyms for the defined keywords were not taken into account. However, it should be mentioned that the selected keywords are the frequently used technical terms in the procurement process of buildings and the application of LCA. Only review and research articles in the English were used for metadata analysis. No gray literature was thus considered. Country-specific documents and documents in languages other than English were therefore not included. Finally, there was another limitation regarding the exclusion and assessment of publications. No assessment of publication bias was made. However, the study selection was performed by two reviewers, thus using the double-check principle to avoid subjective assessment. With regard to the final sample, it must be mentioned that due to the existing research gap, the number of articles within the final sample was not representative. The classified obstacles, therefore, do not claim to be complete.

Future research approaches for the implementation of LCA in the procurement process of buildings must be well planned in order not to limit know-how in terms of the development of greener alternatives of bidders by imposing the mandatory use of LCA. Currently, a GHG emission bonus/malus system is being developed, which foresees a mandatory application of LCA in the course of tendering and awarding. In this bonus/malus system, CO_2-eq. is added to or subtracted from the bid price by means of a CO_2 price as a so-called shadow price. As a results of this more innovative approaches, e.g., green alternatives and solutions, are now being promoted by bidders as a strategy for staying competitive in the future [108,109]. Furthermore, the cooperation of all involved stakeholders, i.e., LCA scientists, CEOs of companies, legislators, and policymakers, is crucial for overcoming the obstacles together.

5. Conclusions

This article summarizes the results of a systematic literature review (SLR) on the application of life cycle assessment (LCA) in the procurement processes of public buildings. The aim was to determine the current state of research on this topic and where the obstacles to implementation occur.

The results show that numerous articles discussed sustainable tendering or green public procurement in the construction industry, however, the LCA method was scarcely used in the procurement process. When examining the obstacles, different solutions can be taken into consideration on distinct levels. The identified obstacles to overcome were summarized within the following five categories (i) methodological obstacles, (ii) organizational obstacles, (iii) legal obstacles, (iv) political obstacles, and (v) economic obstacles.

Concepts for integrating LCA into the procurement process need to be developed, researched, tested, and, most importantly, implemented rapidly in order to reduce further CO_2 emissions caused by the construction industry. Therefore, a mandatory integration of LCA in the procurement process is needed. One effective method for implementing CO_2 emission constraints monetarily is as an award criterion by applying the method of Whole Life Costing, i.e., to calculate externalities.

The obstacles identified show where adjustments need to be made in order to establish the implementation of LCA in the tendering and awarding process for buildings in the future. The results thus contribute to the EU's Climate Target Plan to ensure carbon neutrality by 2050. In the future, so-called carbon budgets for certain construction measures will further support and accelerate the implementation of sustainable construction. In this context, a greenhouse gas emissions bonus/malus system is currently being developed as part of the "Paris Buildings" research project, which will consider selected externalities in the awarding process and promote more environmentally friendly submitted projects. Further efforts for more sustainable procurement will also be essential requirements for the architectural competition. Requesting sustainability aspects at this early stage can be a further lever for implementing sustainable construction.

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Sustainable procurement
Carbon neutrality
Sustainable construction

ABSTRACT

In order to exploit the existing GHG emissions reduction potential of a building in the early design phase, approaches and incentives are needed to promote sustainable procurement already in the tendering and awarding phase. The objective of this study is to develop a Life Cycle Assessment (LCA)-based bonus/malus system for the public procurement of buildings and provide a step-by-step guideline for practical application. GHG emissions are monetized and added to the bid price by using shadow prices to calculate external cost and a results-based climate finance (RBCF) approach to determine a GHG emissions bonus/malus. The results show that under the assumptions of the validation example, a 38 percent reduction in GHG emissions can be achieved at only a 10 percent increase in cost. It can be concluded that the application of the LCA-based bonus/malus system leads to a reduction in GHG emissions and thus combats progressive climate change.

1. Introduction

Increasing greenhouse gas (GHG) emissions are continuing to drive climate change and are becoming ever more of a major global problem. In order to have a 50 per cent change of keeping global warming below 1.5 °C, the remaining cumulative carbon budget should not exceed 500 billion tons of CO_2eq by 2050 (Intergovernmental Panel on Climate Change (IPCC), 2022). With a share of 37% of global operational energy and process-related CO_2 emissions, the construction sector is the largest contributor (United Nations Environment Programme (UNEP), 2022). In order to reduce its emissions, solutions have been continuously developed in science for more than 30 years to decrease either the embodied or the operational emissions during the life cycle stages of buildings (Ibn-Mohammed et al., 2013; S.A. Khan et al., 2022; Kumari et al., 2020; Scherz et al., 2022a; Skillington et al., 2022). Embodied emissions arise in buildings primarily in the manufacturing and construction phase, in the use phase through maintenance and repair and the replacement of materials at the end of their service life and subsequently in the end-of-life phase during dismantling, recycling or landfilling (World Green Buildings Council (WGCB), 2019).

Approaches for the reduction of embodied emissions range among others, from the reduction of masses through more slender load-bearing systems (Habert et al., 2012), through the reduction or replacement of GHG emissions-intensive materials, e.g. through cement reduction and replacement by other binders (Juhart et al., 2019; Valente et al., 2022; J. Zhang et al., 2021), through the use of renewable raw materials such as in particular biogenous materials, such as timber, cellulose, straw (Ahmed et al., 2021; Lo, 2017; Xu et al., 2022), up to the development of sustainable building materials (Mahoutian and Shao, 2016; Salah et al., 2022). Another way to reduce embodied emissions is by not building anything new and opting for adaptive reuse of existing buildings instead (Sanchez et al., 2019; Owojori et al., 2021). Adaptive reuse involves modifying and repurposing existing structures for new uses. By doing so, the environmental impact of new construction materials is avoided, as well as the emissions associated with transportation and disposal of demolished building materials (Langston, 2008; Lanz and Pendlebury, 2022). Furthermore, adaptive reuse can help preserve historic buildings and maintain the character of a neighborhood (Rodrigues and Freire, 2017; Foster, 2020).

In the use phase, embodied emissions are reduced through durable building materials (Ince et al., 2022; Steindl et al., 2020) or also, for example, through the use of materials with extended service lives (Niu et al., 2021; Wang et al., 2022). At the end of the building life cycle, the principles of the circular economy are increasingly being taken into

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account and above all, the use of recycled materials and the reuse of materials are being intensively promoted (Ghaffar et al., 2020; W.S. Khan et al., 2022).

In the use phase, the focus is primarily on reducing energy demands by implementing higher energy standards (D'Agostino et al., 2021; de Masi et al., 2021; S.-C. Zhang et al., 2021) and increasing the efficiency of technical building equipment (Delač et al., 2022; Farouk et al., 2022; Mostafavi et al., 2021). In addition, efforts are increasingly being made to cover energy requirements via solar and photovoltaic systems (Chen et al., 2022; Martín-Chivelet et al., 2022; Vassiliades et al., 2022).

The trend of growing global population and urbanization, however, is complicating the achievement of a carbon-neutral built environment. At present, approximately 55% of the global population resides in urban areas, with projections indicating that this figure will rise to 70% by 2050. Consequently, the construction of about 60% of the necessary housing and settlements is imperative (United Nations, 2018). The construction of these new buildings in turn requires equal, non-discriminatory, mutually recognized and transparent competition through tendering and award procedures (European Parliament, 2014).

In this context and in addition to the aforementioned technology-based solutions, the procurement process of buildings has also evolved in terms of sustainable development. In 2004, the EU Directives 2004/17/EC and 2004/18/EC have provided that contracts may also be awarded on the basis of the most economically advantageous tender (MEAT) next to the lowest price principle (European Parliament, 2004a, 2004b). These directives also marked the beginning of new developments such as green public procurement (GPP). In 2014, in these EU directives as well as in the Austrian Federal Public Procurement Act, in addition to the already permitted MEAT, the tendering and awarding based on Life Cycle Costing (LCC) as well as the consideration of external cost, which can be calculated by the life cycle assessment (LCA) method, were also included (European Parliament, 2014; Federal Procurement Act, 2018). In Austria, all public awarding authorities and sector awarding authorities are bound by the Federal Public Procurement Act when awarding construction projects. As in the EU Directives of the European Parliament, the Federal Procurement Act also allows the award of contracts based on the MEAT. In the Federal Procurement Act, the award of contracts according to the MEAT is mentioned in §142 para. 1. In accordance with §2 para. 22, inclusion of the MEAT principle in the awarding of contracts must be specified in the tender documents. In addition, the award criteria defined by the awarding authority in proportion or, exceptionally, in the order of their importance, which are non-discriminatory and related to the subject matter of the contract, or the underlying cost model (§91 para. 4) for determining the MEAT offer must be specified (Federal Procurement Act, 2018). The entire process as well as the underlying requirements of tendering and awarding of construction projects in Austria are regulated in the Federal Procurement Act (Federal Procurement Act, 2018) as well as in the standard ÖNORM A 2050 (Austrian Standards International, 2006) and ÖNORM B 2110 (Austrian Standards International, 2013). In addition to the legislative frameworks, recent policies have also encouraged environmental and social tendering and awarding of contracts in public procurement (Dragos and Neamtu, 2014).

Despite the progressive advancements in sustainable procurement practices for buildings over the years, the tendering and awarding process continues to prioritize the principle of awarding contracts on the basis of the lowest price. In the context of MEAT, while there are numerous studies in the literature that include environmental requirements in the award of buildings (Jalaei et al., 2022), these environmental requirements include, among others, the environmental management system, the environmental knowledge of the bidders, the handling of the environmental aspects described in the environmental plan and also the machinery used or the energy use in the completed building. Furthermore, waste disposal and emissions to water during construction, reduction of pollutants or requirements for the working environment are mentioned in the literature as environmental requirements for the award (Polonsky et al., 2022; Varnäs et al., 2009). Nevertheless, in most of the studies the main awarding criterion is the price and other award criteria are often too weakly weighted and have little impact on the award decision.

The importance of considering both embodied and operational emissions in building design for improving the environmental performance is highlighted in the study of Gauch et al. (2023). Despite operational emissions receiving more attention, embodied emissions can contribute significantly to a building's lifetime emissions. To reduce both construction cost and embodied emissions, the study recommends designing buildings to be more compact, using materials with a lower carbon footprint, and minimizing waste during construction. The authors conducted a LCA and observed that minor design modifications could substantially decrease embodied emissions without incurring additional cost. Therefore, it is crucial to consider both types of emissions in building design to create a more sustainable built environment (Gauch et al., 2023). Additionally, the authors propose in another study a carbon vs. cost option mapping tool that can help designers make informed decisions considering both environmental and economic factors. The tool assists designers in identifying cost-effective and low-carbon alternatives while balancing the trade-offs between GHG emissions and cost. (Gauch et al., 2022). Good early-stage design decisions, as highlighted in the study of Dunant et al. (2021), can reduce embodied emissions by up to 50% and lower structural frame cost (Dunant et al., 2021).

To evaluate the environmental performance of buildings, i.e., to assess environmental requirements such as the reduction of GHG emissions, the method of LCA has become established. Although numerous studies have shown that the application of LCA in the construction industry is a strategy to reduce environmental impacts (Cabeza et al., 2014; Soust-Verdaguer et al., 2016) and the inclusion of LCA into government procurement is also proposed within a theoretical framework (Jalaei et al., 2022). Despite several studies highlighting the effectiveness of LCA in reducing environmental impacts in the construction industry (Cabeza et al., 2014; Soust-Verdaguer et al., 2016), proposals to include LCA in government procurement frameworks (Jalaei et al., 2022), and the approval of life cycle-oriented cost models in EU directives and the Austrian Federal Procurement Act, the practical application of LCA in the building tendering and award process is rare. This is also supported by the limited number of studies investigating the implementation of LCA in procurement procedures (Du et al., 2014; Francart et al., 2019; Fuentes-Bargues et al., 2017; Ng, 2015; Vidal and Sánchez-Pantoja, 2019). Furthermore, a recent report launched by the European Commission, analyzing real tenders and court cases on the use of LCA-based criteria throughout the procurement process, also underpins this argument (European Commission et al., 2021). Moreover, a recently published review study shows that especially the consideration of GHG emissions is a research gap at this early stage and that LCA is scarcely applied in the procurement process of buildings due to various implementation obstacles such as methodological, organizational, legal, political and economic barriers. One of the barriers identified in the review study is the lack of clear rules and guidelines for implementing LCA in the building procurement process (Scherz et al., 2022c).

As stated by the International Energy Agency's Energy in Building and Communities Programme (IEA EBC), the tendering and award procedures for buildings must be further developed in order to meet the requirements of a carbon-neutral environment (International Energy Agency's Energy in Building and Communities Programme (IEA EBC) Annex 72, 2021). In order to contribute to this further development and thus address the problem of insufficient implementation of LCA in the building procurement process due to a lack of guidance and award models, the objective of this study is thus to develop a framework, i.e., the LCA-based bonus/malus system, to internalize GHG emissions of buildings in the bid price, in order to take into account, the environmental performance of buildings when awarding contracts on a pure price basis. This article addresses two main research questions.

1) What strategies can be employed to conduct a Life Cycle Assessment (LCA) of tendered buildings and integrate it into the awarding decision process?
2) How does the inclusion of monetization of buildings' GHG emissions in the procurement process affect the ranking of bidders?

To answer these questions, we modeled a validation example with seven bids based on literature values for building construction cost and global warming potential (GWP). By applying the LCA method we evaluated the environmental impacts of the bidder offers We then monetized GHG emissions using two internal carbon pricing instruments, i.e., a shadow price and an RBCF approach. In addition, we included the environmental externalities, also referred to as external cost, in the seven bid prices and awarded the contract according to Paris-compatible cost (PCC) scenarios by applying the developed LCA-based bonus/malus system. The LCA-based bonus/malus system is based on the Austrian Federal Procurement Act and therefore addresses the application in the Austrian building procurement process. However, the theoretical framework and the individual implementation steps can be applied to other national conditions.

The novelty of this study stems from the developed LCA-based bonus/malus system, which allows awarding contracts according to the lowest price taking into account the environmental performance of buildings through external cost. In addition, the study presents a monetary project-oriented remuneration and compensation system, which is also taken into account in the course of the award by means of the LCA-based bonus/malus system through the so-called GHG emissions bonus/malus. This paper aims to make a significant step forward in the sustainable procurement of buildings by encouraging bidders to implement innovative sustainable construction projects, e.g. through new, innovative construction methods, and to map their environmental advantage over conventional tendering and award processes.

2. Material and methods

In this section, the implemented methods of the LCA-based bonus/malus system are briefly explained to ensure transparent traceability and reproducibility of the findings. Furthermore, the developed LCA-based bonus/malus system is placed in the context of the Austrian procurement process for buildings.

2.1. Life cycle assessment (LCA)-based bonus/malus system

The cost model developed for awarding according to the most favourable price, taking into account the environmental performance of buildings, i.e., GHG emissions, is called LCA-based bonus/malus system. The model combines the methods of cost calculation within the offer preparation, i.e., construction cost or LCC, internal carbon pricing instruments, i.e., shadow pricing and a RBCF approach, and the LCA method. In detail, this means that the award is made according to the lowest price after application of the LCA-based bonus/malus system, i.e., an award according to PCC scenarios. The monetized environmental externalities can be included either in the construction cost or (if available) in the LCC. When construction cost are calculated in the offer preparation, the construction cost are extended by adding external cost to environmental construction cost (eCC). When LCC are calculated in the preparation of the offers, the LCC, i.e., construction cost, operating cost, maintenance cost and end-of-life cost, as defined in EN 16627, EN 15643–4 and ISO 15686–5 (CEN/TC 350 2012; CEN/TC 350 2015; International Organization for Standardization, 2008), are extended by the external cost to environmental Life Cycle Cost (eLCC) as defined by Ciroth et al. (2008) (Ciroth et al., 2008).

Finally, the GHG emissions bonus or malus is added or subtracted based on the GHG emissions mean value of all submitted bids. Fig. 1 shows the calculation principles for calculating the GHG emissions bonus/malus.

$$\text{GHG emissions}_{BONUS/MALUS}\ [€] = \left(GWP_{\_n}\ [t\ CO_2 eq] - \frac{\sum_1^n GWP_{BIDDER}}{n}\right) \text{ x } RBCF_{carbon\ price}\ [€/tCO_2\ eq]$$

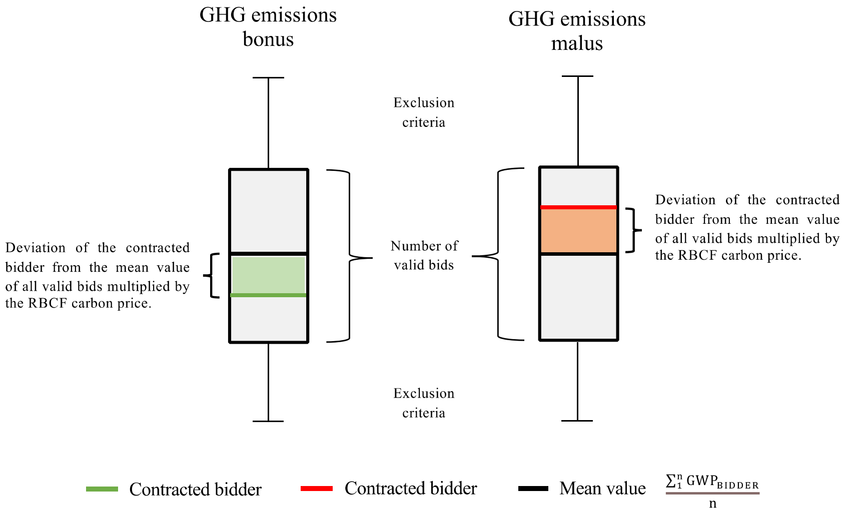

Fig. 1. Calculation principle for calculating the GHG emissions bonus/malus.

Parallel to the application of the developed cost model, other award criteria can also be defined, individually weighted and thus taken into account in the award process. Fig. 2 shows the theoretical framework of the LCA-based bonus/malus system. In general, awarding authorities can choose between the constructive and the functional performance specifications. The differences between these two performance specifications in relation to the LCA-based bonus/malus system are described in section 3.1. Regardless of the two options, both processes end in a complete performance specification including bills of quantities and unit prices. Based on the bills of quantities and the unit prices construction cost, LCC and GHG emissions can be calculated. The equations for the LCA-based bonus/malus system can also be found in Fig. 2.

Since the focus of this article is not on the calculation of construction cost, LCC or GHG emissions, but purely on the presentation and validation of the developed LCA-based bonus/malus system, fictitious construction cost and GHG emissions values were assumed for the further calculations. While in this study the applicability of the cost model based on construction cost is investigated, the application of the model considering LCC was analyzed in the study of Scherz et al. (2023) (Scherz et al., 2023).

Therefore, no explanations on system boundaries, reference study period (RSP), assumptions in the individual life cycle modules or assumed service lives are given. Furthermore, detailed descriptions of the calculation of the construction cost and the LCA framework, i.e., cost categories, unit prices, goal and scope, life cycle inventory, impact assessment and interpretation, are not provided. Therefore, for the transparent presentation of the individual process steps of the LCA-based bonus/malus system, out of cost perspective only brief descriptions of the bid preparation based on the construction cost (as applied in this study) and the possible application of the cost model based on LCC (not applied in this study) are given. Out of the environmental perspective a brief description of the LCA method is given.

2.2. External cost over a building life cycle

External costs are defined in ISO 15686–5 as quantifiable costs or benefits that arise when the actions of organizations and individuals have an impact on people other than themselves. The goal of including external costs is to make decisions not only on the basis of market efficiency, but also to consider the wider impact of an economic decision on society in its entirety (International Organization for Standardization, 2008). A common government approach for dealing with external costs is to impose regulatory taxes on a negative external cost and to provide subsidies for the external benefits. These are tangible costs that can be readily included in a eLCC approach (Ciroth et al., 2008).

In our market-oriented, competitive and monetized society, a fundamental starting point for considering environmental damage cost is the monetary equivalent of external environmental damage. There are two different theoretical approaches to monetize these external environmental damages, the damage cost approach and the abatement cost approach. The damage cost approach estimates the damages caused by environmental externalities and assigns a monetary value to these damages or values these damages. In the abatement cost approach, the focus is not on the cost of the damage caused, but on the cost of prevention. It is agreed in advance, i.e., without yet knowing all the cause-effect relationships exactly, on certain preventive measures. The cost incurred by these measures are known as prevention cost (Adensam et al., 2002). ÖNORM EN ISO 14007:2021 and ÖNORM EN ISO 14008:2021 form the normative basis for the standardized calculation of environmental cost and benefits in the EU (Austrian Standards International, 2021a, 2021b). ÖNORM EN ISO 14008:2021 clearly regulates how environmental cost are to be calculated and which monetary valuation methods are to be applied. The calculation of external cost based on the monetization of GHG emissions using carbon pricing instrument can be classified as monetary valuation study according to ISO 14008 (Austrian Standards International, 2021b). Table 1 shows the definitions for the general requirements for a monetary valuation study according to ISO 14008.

The aim of this monetary evaluation is to take into account the environmental performance of a building in the comparison of bid prices of different bidders. The conversion of building-related emissions, i.e., embodied and operational emissions, is calculated on the basis of a defined shadow price. The building-related emissions are determined using the LCA method based on the submitted performance specifications of the participating bidders. The calculated monetary value is then added to the bidders' bid prices.

The target group thus includes public-sector clients in the Austrian construction industry, such as cities and municipalities, as well as contractors who submit bids on the basis of tendered performance specifications. Although this article focuses on the Austrian construction industry, ongoing climate change is a global problem. With the practical application of the proposed LCA-based bonus/malus system, Austria can act as a role model in the transition to a net zero carbon-built environment. After regional application and validation, the intended effects of

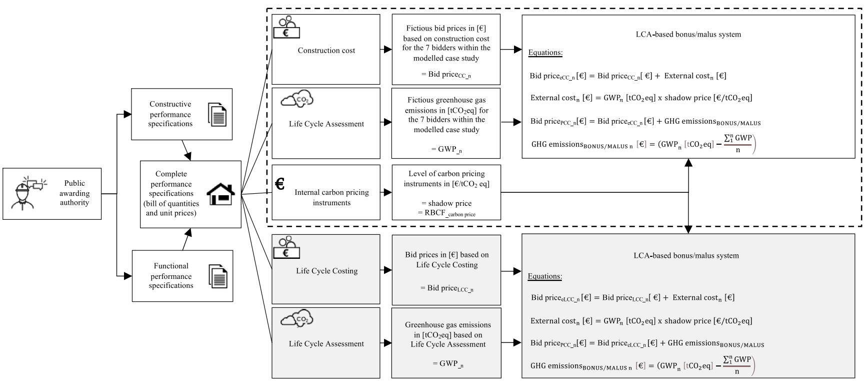

Fig. 2. Theoretical framework of the LCA-based bonus/malus system highlighting the methodological approaches and the equations. The framed box represents the content of this study, which examines bid prices based on construction cost. The application of the LCA-based bonus/malus system by means of bid prices based on LCC (gray boxes) was investigated in Scherz et al. (2023) (Scherz et al., 2023).

Table 1
General requirements for a monetary valuation study (Austrian Standards International, 2021b).

General requirements according to ISO 14008	Definitions
Currency of the monetary value	€
Base year of the monetary value	2023
Time period of the monetary value	One-time
Reference unit of monetary value	Building
Whether and how the monetary value is aggregated	GWP [tCO2eq/a] x shadow price [€/tCO_2eq] and GHG emissions bonus/malus x RBCF carbon price [€/tCO_2eq] are included in the bid prices [€]
Whether and how a value transfer is carried out	No value transfer
Whether and how the monetary value is equity weighted	Not equity weighted
Whether and how the monetary value is discounted	Not discounted
Whether and how uncertainty and confidence intervals are Quantified and sensitivity analysis is carried out	Sensitivity analysis is considered by using carbon price ranges (50 €/t CO_2eq to 400 €/t CO_2eq)
Whether the monetary value is a marginal, average or median measure	Based on shadow price range and price range of RBCF carbon price

the GHG emissions reduction can be multiplied globally.

In addition to the general requirements, specific requirements must also be specified for the environmental indicators considered in the study. Table 2 shows the definitions for the specific requirements according to ISO 14008.

The approximation for economic values is assessed based on the "market prices of traded goods and labour" procedure. This procedure reflects the common practice of bidding by bidders based on a performance specification. The aim of this article is to introduce a novel methodology for incorporating external cost arising from GHG emissions generated by buildings into the procurement process. The external costs are thus limited to the GWP indicator and are monetized with a defined shadow price.

Table 2
Specification of the environmental impact or aspect for a monetary valuation study (Austrian Standards International, 2021b).

Specification of the environmental impact or aspect according to ISO 14008	Definitions
Whether an increase or a decrease in the environmental impact or aspect is valued	Increase of GWP [tCO_2eq/a] in the Austrian building sector.
the spatial extent and resolution of the environmental impact or aspect that the monetary value is to be valid for	
The temporal extent and resolution of the environmental impact or aspect that the monetary value is to be valid for	Valid from the announcement of tender documents until submission deadline of offers
The environmental impact pathway(s) included in the study and the model(s) used	IPCC climate path scenario 1.5 °C (50% change)
The indicator(s) by which the environmental impact or aspect is measured	GWP
The unit and quantity of environmental impact or aspect that the monetary value of The study is to be estimated for	tCO_2eq/a
The context of the environmental impact or aspect, to the extent that it influences the monetary values obtained from the study	In general life cycle modules A1-A5, B4, B6 and C1–C4 based on the LCA methodology. In this study GWP values based on literature benchmarks

2.3. Life cycle assessment

The LCA method can be used for the calculation of environmental impacts. The LCA method is based on the ISO 14040 and the ISO 14044 standards (Austrian Standards International, 2006b, 2009). The four phases of LCA are (i) definition of goal and scope, (ii) inventory analysis, (iii) impact assessment and (iv) interpretation of results. Especially in the construction industry, LCA has been well established for decades and has also been anchored in EN 15978 (Austrian Standards International, 2011). In addition, the EU directive 2014/24/EU proposes the LCA to calculate external cost within the MEAT principle (European Parliament, 2014). For the application of the LCA-based bonus/malus system, the conducted LCA must include embodied emissions as well as operational emissions. Therefore, the building life cycle has to be modeled according to the European standard EN-15978 (CEN, 2011). The system boundary considers the life cycle modules of the production stage (A1-A3), the modules of the construction process stage (A4-A5), the module of replacement (B4), the module of operational energy consumption (B6), and the end-of-life modules of demolition (C1), transportation (C2), waste treatment (C3), and disposal (C4). The environmental impacts of the production stage modules (A1-A3) and the end-of-life modules (C3, C4) are based on the material quantities described in the performance specifications. Due to the lack of information in the tendering and awarding phase, the impacts of module construction (A5) and module demolition (C1) can account for 5% and 2% of the module impacts from the product phase (A1-A3), respectively (Hoxha et al., 2016). The environmental impacts of replacing materials and components during the RSP (50 years) are considered in the module replacement (B4) and calculated based on the service life data of components. The impact of the use phase is taken into account in the module operating energy consumers (B6) and is based on the calculations of the energy performance certificates.

The data sets of ökobau.dat (Federal Ministry for Housing, Urban Development and Building, 2020) can be used for calculating the environmental impacts of the GWP as required by the German Sustainable Building Council (germ. Deutsche Gesellschaft für Nachhaltiges Bauen, DGNB). Environmental impacts are evaluated based on the defined functional unit as square meters of net floor area (m^2 NFA) over the defined RSP.

2.4. Carbon pricing instruments

In addition to the calculation of GHG emissions from buildings using LCA, monetary values must also be determined in order to be able to internalize the GHG emissions as proposed in the eLCC. In the course of the LCA-based bonus/malus system, the shadow price and the RBCF carbon price are applied in this context. Both instruments represent internal carbon pricing instruments in order to avoid double-accounting with already existing carbon pricing instruments in Austria such as emission trading system (ETS) and carbon tax.

The shadow price is an internal and voluntary pricing instrument for carbon in cost-benefit analyses of projects and thus represents a monetary value that can be used to calculate external cost (Smith, 1987). Shadow prices are commonly based on a number of assumptions due to the lack of robust data, making them subjective (Hayes, 2021). The shadow price is based on the literature values for carbon prices and lies in an assumed range of 50 €/tCO_2eq to 400 €/tCO_2eq (CCCA-Expert_innen, 2020; de Nocker and Debacker, 2018; Nydahl et al., 2022, 2019; Pindyck, 2019).

The internal carbon pricing instrument RBCF, on the other hand, is based on defined project outcomes, e.g. through set minimum GHG emissions or other benchmarks for environmental indicators. For the calculation of the GHG emissions bonus/malus, this defined benchmark represents the mean value of the GHG emissions of all submitted offers. The deviations of the GHG emissions of an offer from this mean value are monetized by means of the RBCF carbon price, similar to the calculation of external cost (see Fig. 1). As with the shadow price, values from 50 €/tCO_2eq to 400 €/tCO_2eq are used for monetization.

2.5. Environmental exclusion criterion

A particular characteristic of the LCA-based bonus/malus system is that an environmental exclusion criterion, i.e., a minimum value for GHG emissions in $kgCO_2eq/m^2_{NFA}$, is set. In recent years, several studies have been published analyzing benchmarks for embodied and operational emissions of buildings. In this context, a recently published study, examined more than 650 case studies and showed that the values vary depending on the building type and the energy performance class (Röck et al., 2020). In the development of benchmarks, methodological issues such as top-down or bottom-up approaches or calculation rules are also examined and further developed in particular (Balouktsi and Lützkendorf, 2022; Frischknecht et al., 2019; Hollberg et al., 2019).

In this study, we used the benchmarks of the DGNB building certification system defined in the LCA criterion. In the DGNB building certification system, the GWP of buildings can be compared with three benchmark values, i.e., the target value, the reference value and the limit value. For different building typologies (building schemes), i.e., office buildings, educational buildings, residential buildings, the DGNB building certification system also provides different benchmark values for the embodied and operational emissions. Table 3 shows an excerpt of the GWP benchmarks.

As explained later in section 3.2, notional GWP values are assumed for the modeled validation example, which lie between the target value and the reference value of the building schemes office and educational buildings, i.e., between 13,33 $kgCO_2eq/m^2_{NFA}$ and 27,72 $kgCO_2eq/m^2_{NFA}$.

All methodological principles, such as e.g. scope of LCA, description of the assessed building, calculation rules for the building model, requirements for data, reporting and presentation of results, of the LCA method of the Austrian Sustainable Building Council are explained in the DGNB building certification system (Austrian Sustainable Building Council, 2020).

3. Life cycle assessment (LCA)-based bonus/malus system

In this section, the developed framework of the LCA-based bonus/malus system is presented, and its application is explained on the basis of individual implementation steps. At the end of this section, the required assumptions for the modeled validation example are defined.

3.1. Framework and process steps

The application of the LCA-based bonus/malus system requires an adaptation of the current tendering and awarding processes for buildings. In particular, the following seven process steps must be taken into account.

Step 1: Definition of the type of the applied performance specification

In the case of a tendering with constructive performance specifications the awarding authority must define a detailed performance target according to ÖNORM B 2110 (Austrian Standards International, 2007). Furthermore, next to the definition of suitability criteria, selection criteria (in the case of a two-stage award procedure) and award criteria, the awarding authority is responsible for the design of the building and the preparation of a detailed bill of quantities, i.e., service items and quantity determination. Based on the tender documents, bidders prepare their main offers by providing unit prices for each service item. After the bid deadline, the bids are opened, checked and the contract is awarded on the basis of the defined award criteria.

By choosing this type of tendering, changes or modifications by the bidders in the tender documents and in the bill of quantities are not permitted. If changes are made, this leads to the exclusion of the bid. However, the Federal Procurement Act also permits the submission of other, better, more innovative or more favourable solutions by bidders in the form of alternative offers, which will make the existing know-how of the bidders available to the awarding authority. Alternative offers must be expressly permitted by the awarding authority. In addition, it must be specified whether these are permitted together with the main bid or also in isolation (Federal Procurement Act, 2018).

In the case of a tendering with functional performance specifications the awarding authority has to define the performance target according to the Federal Procurement Act (§ 103 para. 3 and § 104 para. 2) as well as the suitability criteria, selection criteria (in the case of a two-stage award procedure) and award criteria. Based on the defined performance target, the bidders are responsible for the design of the building and the preparation of the main offer. This allows innovative ideas and the inclusion of know-how of the bidders to be taken into account. After receipt of the bids and expiry of the bid deadline, the bids are checked, as in the case of the constructive performance specification, and the contract is awarded on the basis of the award criteria.

Irrespective of the performance specification type, additional specifications must be provided by the awarding authority for the application of the LCA-based bonus/malus system. The contracting based on the price should be chosen as the award criterion, since the environmental performance of the buildings is included in the bid price by means of the calculated GHG emissions and the monetization through a shadow price and a RBCF carbon price. In order to enable the bidders to calculate the GHG emissions, all calculation principles of the LCA as well as the level of the carbon prices must be specified in the tender documents. When selecting the constructive performance specification, the awarding authority must also explicitly allow alternative offers for decisive building components in order to give bidders the opportunity to provide their own ideas and know-how. After opening the bids, the awarding authority must evaluate the GHG emissions of the submitted bids to check the results. Afterwards the awarding authority must monetize them with the shadow price and calculate the GHG emissions bonus/malus with the RBCF carbon price for each bid. If the know-how for conducting an LCA is not available within the awarding authority, external sustainability assessment experts must be consulted for the verification of the LCA calculations. Finally, the calculated external cost must be added or subtracted from the bidder's prices. Fig. 3 shows the spheres of awarding authorities and bidders for the two performance specification types, as well as the detailed tender specifications for the application of the LCA-

Table 3
GWP target values, reference values and limit values for different buildings schemes divided in embodied and operational emissions in kg CO_2eq/m^2_{NFA} x a (Austrian Sustainable Building Council, 2020).

Building schemes	Target value		Reference value		Limit value	
	Embodied emissions	Operational emissions	Embodied emissions	Operational emissions	Embodied emissions	Operational emissions
Residential buildings	5,17	5,70	9,40	14,95	13,16	20,94
Office buildings	5,17	8,16	9,40	18,32	13,16	25,64
Educational buildings	5,17	8,16	9,40	18,32	13,16	25,64
Hotels	5,17	14,63	9,40	39,97	13,16	55,96
Logistic buildings	6,60	11,75	12,00	26,37	16,80	36,91

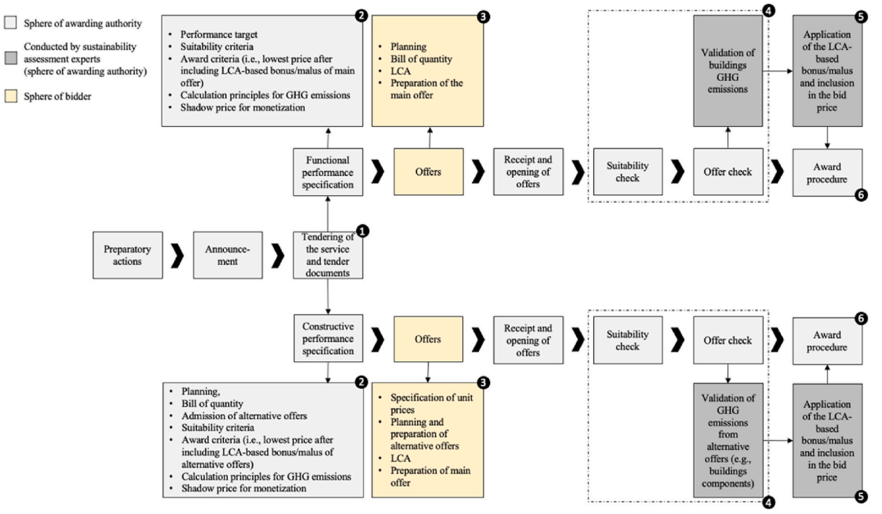

Fig. 3. Spheres of awarding authorities and bidders for the two tender types (i) tender with functional performance specifications and (ii) tender with constructive performance specifications, as well as the detailed tender specifications for the application of the LCA-based bonus/malus system.

Step 2: Indication of the necessary additional information required in the tender documents.

based bonus/malus system. In addition, the individual process steps for applying the LCA-based bonus/malus system are highlighted.

As mentioned, all necessary calculation principles and information must already be provided to the bidders in the tender documents in a transparent and comprehensible way in order to apply the LCA-based bonus/malus system.

The standards ÖNORM EN 15978 and ÖNORM EN 15804 should be defined (Austrian Sustainable Building Council, 2020; 2011) for the calculation basis of the LCA. In this context, the four phases (i) definition of goal and scope, (ii) life cycle inventory, (iii) impact assessment, and (iv) interpretation are to be carried out within the LCA. The system boundary is captured within the goal and scope of the study and, with respect to the developed LCA-based bonus-malus system, includes the entire building under consideration, excluding outdoor facilities. If individual building services are accounted for, the system boundaries must be clearly defined during the bidding process. For the LCA-based bonus-malus system, the goal and scope of investigation includes the mandatory declaration of modules A to module C according to ÖNORM EN 15804 (Austrian Standards International, 2022).

In the life cycle inventory (LCI), the input data are collected on the basis of databases. The latest version of the respective database must be used for the tendering of services. Various databases are currently available for conducting LCAs. As an example, in the course of the LCA-based bonus-malus system, the application of the database ökobau.dat is proposed for conducting the LCA (Federal ministry for housing urban development and construction, 2022). This sustainable construction information portal is made freely available by the German Federal Ministry of the Interior, Building and Community. The database currently includes about 900 data sets for different building products and is compliant with ÖNORM EN 15804. If no suitable LCA data are available for materials or components, a technically similar dataset must be used. For these reasons, (external) verification of the conducted LCAs is mandatory. For LCA data that do not originate from the applicable database, compliance with the methodological requirements of EN 15804 must be ensured and documented by the bidders.

According to the criteria for disregarding inputs and outputs outlined in the ÖNORM EN 15804, a cut-off criterion of 1% of the overall process mass must be satisfied if there is not enough input data available for individual processes. Furthermore, the combined total of disregarded input flows, such as those within life cycle modules, should not exceed 5% of the overall energy and mass input (Austrian Standards International, 2022).

This means that in the product stage (modules A1 to A3), all materials that exceed a defined threshold value (e.g. greater than 1% of the total mass of the building) must be accounted for. In total, no more than 5% of the mass of the entire building may be neglected. In the use stage, materials or components to be replaced (module B4) within the RSP of 50 years are to be considered on the basis of service life catalogues (Gebäudeausrüstung, 2003; Landesverband Steiermark und Kärnten, 2020). In module B6, the dataset for the used energy source for coverage of the energy demand has to be applied. The used foreground and background data shall be presented transparently within the bidding process and the results of the LCA shall be reported accordingly.

In the impact assessment, the environmental indicator GWP in tCO_2eq is used and converted to the NFA in m^2 per year. During interpretation, the results must be compared with the valid GWP mean value and the deviation must be indicated.

Existing scientific literature was utilized to establish the shadow prices for external cost calculations and the RBCF carbon prices for calculating the GHG emissions bonus/malus. Various studies have been conducted to determine carbon prices (De Nocker and Debacker, 2018; Arendt et al., 2020; Rennert et al., 2022). For this particular study, the carbon price range was set from 50 €/tCO_2eq to 400 €/tCO_2eq, based on information provided by the CCCA experts' factsheet (CCCA experts 2020). Notably, the initial value of 50 €/tCO_2eq is similar to the average value of carbon prices in the EU (The World Bank 2021). However, any other specified shadow prices outside this range are also applicable.

For the calculation of the GHG emissions bonus/malus, a carbon price must be specified for the application of the RBCF approach. The specified carbon price in the course of the RBCF approach does not have to be identical to the shadow price. Like the shadow price, this can also lie in the range from 50 €/tCO_2eq to 400 €/tCO_2eq.

An environmental exclusion criterion, i.e., an environmental knock-out criterion that excludes bids if they do not fulfill that criterion, must also be defined. In the LCA-based bonus/malus system, this criterion is a benchmark for GWP in kgCO_2eq/m^2_{NFA} x a divided into a benchmark for embodied emissions and for operational emissions. There are numerous proposals in the literature for the level of these benchmarks for different building typologies. For the first validation of the LCA-based bonus/malus system, the benchmarks of the DGNB building certification system are used. These are for the building type office and educational buildings 9.40 kg CO_2eq/m^2 $_{NFA}$ x a for embodied emissions and 18.32 kg CO_2eq/m^2 $_{NFA}$ x a for operational emissions (Austrian Sustainable Building Council, 2020).

Step 3: Life cycle assessment within bid preparation.

Depending on the selected type of performance specification, in the third step the bidders develop alternative solutions for the approved alternative bids within the constructive performance specification or develop solutions for the entire building within the functional performance specification. Regardless of the two types, LCA based on the requirements in the tender documents must be conducted in the course of the bid preparation.

Step 4: Validation of offers.

After receipt of the bids and the end of the bid deadline, the bids must be evaluated. In addition to the steps carried out as before in the course of the bid evaluation or the in-depth bid evaluation, the LCA calculation steps and results in particular must be checked when the LCA-based bonus/malus system is applied. If the know-how for this validation is not available within the awarding authority, it is recommended to consolidate external sustainability assessment experts. Before the LCA calculation steps and results are checked in detail, the comparison with the environmental minimum criterion takes place and offers that do not fulfill this knock-out criterion are excluded. Afterwards, the individual LCAs of the bidders are checked.

Step 5: Calculation of external cost and consideration of GHG emissions bonus/malus.

After the LCA results have been checked, they are monetized by means of the defined shadow price. These external costs are then added to the bid price. Already at this stage, changes in the order of bidders may occur. Subsequently, the mean value of the GHG emissions of all submitted and valid bids is calculated and the deviations of the individual bids from this mean value are calculated. Using this RBCF approach, a GHG emission bonus/malus can be calculated by monetizing deviations from the GWP mean value with the RBCF carbon price. The GHG emissions bonus/malus is added to or subtracted from the bid price in the same way as the external cost.

Step 6: Awarding according to the LCA-based bonus/malus system

The award decision is made on the basis of the lowest price after applying the LCA-based bonus/malus system, also referred to as awarding according to PCC scenarios. The bidder with the lowest bid price$_{PCC_n}$ after the application of the LCA-based bonus/malus system is awarded the contract. However, since this bid price$_{PCC_n}$ is only a fictitious price, all construction works are invoiced according to the initially submitted bid price$_{_n}$.

3.2. Validation example assumptions for the LCA-based emissions bonus/malus system

In the modeled validation example, it is assumed that seven bids were submitted from different bidders. Regardless of the type of performance specifications, i.e., constructive or functional, it is assumed that all formalities such as the timely submission of the bids, the completeness of the bids, and the suitability check are fulfilled for all bidders. For a simplified explanation of the LCA-based bonus/malus system, it is assumed that for the 7 bidders the GHG emissions of the bids have been calculated by the bidders or by consulted external sustainability assessment experts. The chosen GHG emissions are notional values based on the GWP benchmark range between the target value (13.33 kgCO_2eq/m^2_{NFA} x a) and the reference value (27.72 kgCO_2eq/m^2_{NFA} x a) of the DGNB building certification system for office and educational buildings.

For the estimation of the bid prices values between approx. 1,800 to 2,200 €/m^2_{NFA} are assumed based on the “BKI construction cost” (Baukosteninformationszentrum für Architekten, 2022) and multiplied with the tendered building NFA of 5,000 m^2. Furthermore, the carbon prices, i.e., both the shadow price and the RBCF carbon price, were defined based on the literature values and were used to monetize the environmental impacts. The final bid prices as well as the GHG emissions of the bids and the defined carbon prices for two different scenarios are shown in Table 4.

4. Results and validation

Based on the developed theoretical framework of the cost model for sustainable procurement for carbon neutrality of buildings and on the defined assumptions for the validation example, this section presents the results of the modeled validation example and validates the application of the so-called LCA-based bonus/malus system.

4.1. Application of the LCA-based bonus/malus system

After the submission period has ended and the bidders have determined the GHG emissions in the course of preparing their offers and submitting their bids, the awarding authority or consolidated external experts for sustainability assessment review the bids and the LCA results. Bids that exceed the defined environmental minimum criterion are excluded. Finally, the external cost are determined based on the defined shadow price and are then added to the bid price to obtain the environmental (construction cost-based) bid price (bid price$_{eCC_n}$).

$$\text{Bid price}_{eCC\_n}\ [€] = \text{Bid price}_{\_n}[€] + \text{External cost}_{\_n}[€]$$

where:

$$\text{External cost}_{\_n}\ [€] = GWP_{\_n}\ \left[\text{t CO}_2\text{eq} / m^2_{NFA}\ \text{a}\right]\ \text{x shadow price}\ [€ / \text{tCO}_2\text{eq}]$$

Two calculation examples with different shadow prices are presented below as a means of better illustrating the influence of the shadow price and for a better understanding of the developed cost model. Table 5 compares seven bidders and their bid prices with the calculated GHG emissions. In the first validation scenario, a shadow price of 400 €/tCO_2eq is assumed, and in the second validation scenario (see Table 6) a shadow price of 50 €/tCO_2eq is assumed.

Table 5 shows that at a shadow price of 400 €/tCO_2eq, the bidder with the lowest initial bid price (=bid 2), after taking into account the external cost (GWP x shadow price), bidder 2 only occupies second place, while bid 6 becomes the bidder with the lowest environmental bid price. The relative share of external cost in the bid price$_{_n}$ ranges between 16 and 28 percent.

In Table 6, the shadow price is reduced to 50€/tCO_2eq to illustrate the influence of the shadow price. In this example the ranking of the bidders (bid price$_{_n}$ vs. bid price$_{eCC_n}$) does not change because the

Table 4
Validation example assumptions for the LCA-based bonus/malus system.

	Bid price_ [€]	GWP [kg CO_2eq/m² NFA a]	NFA [m²]	RSP [a]	GWP [t CO_2eq]	Carbon price scenario 1 [€/tCO_2eq]	Carbon price scenario 2 [€/tCO_2eq]	External cost scenario 1 €	External cost scenario 2 €
Bid 1	10,370,041	23	5,000	50	5,750	400	50	2,300,000	287,500
Bid 2	9,020,200	24	5,000	50	6,000	400	50	2,400,000	300,000
Bid 3	9,433,478	26	5,000	50	6,500	400	50	2,600,000	325,000
Bid 4	10,821,849	18	5,000	50	4,500	400	50	1,800,000	225,000
Bid 5	10,068,947	22	5,000	50	5,500	400	50	2,200,000	275,000
Bid 6	9,433,273	15	5,000	50	3,750	400	50	1,500,000	187,500
Bid 7	10,811,394	20	5,000	50	5,000	400	50	2,000,000	250,000

Table 5
Scenario 1: Bid priceeCC with a shadow price of 400€/tCO2eq, NFA 5,000 m², RSP 50 years.

	Bid price [€]	GWP [kgCO_2eq/m²$_{NFA}$ a]	GWP [tCO_2-eq]	External cost [€]	Bid price$_{eCC}$ [€]	Share external cost/bid price [%]
Bid 1	10,370,041	23	5,750	2,300,000	12,670,041	22%
Bid 2	**9,020,200**	**24**	**6,000**	**2,400,000**	**11,420,200**	**27%**
Bid 3	9,433,478	26	6,500	2,600,000	12,033,478	28%
Bid 4	10,821,849	18	4,500	1,800,000	12,621,849	17%
Bid 5	10,068,947	22	5,500	2,200,000	12,268,947	22%
Bid 6	**9,433,273**	**15**	**3,750**	**1,500,000**	**10,933,273**	**16%**
Bid 7	10,811,394	20	5,000	2,000,000	12,811,394	18%

Table 6
Scenario 2: Bid price$_{eCC}$ with a shadow price of 50€/tCO_2eq, NFA 5,000 m², RSP 50 years.

	Bid price [€]	GWP [kgCO_2eq/m²$_{NFA}$ a]	GWP [tCO_2eq]	External cost [€]	Bid price$_{eCC}$ [€]	Share external cost_/bid price [%]
Bid 1	10,370,041	23	5,750	287,500 €	10,662,541 €	3%
Bid 2	**9,020,200**	**24**	**6,000**	**300,000 €**	**9,320,200 €**	**3%**
Bid 3	9,433,478	26	6,500	325,000 €	9,758,478 €	3%
Bid 4	10,821,849	18	4,500	225,000 €	11,046,849 €	2%
Bid 5	10,068,947	22	5,500	275,000 €	10,343,947 €	3%
Bid 6	**9,433,273**	**15**	**3,750**	**187,500 €**	**9,620,773 €**	**2%**
Bid 7	10,811,394	20	5,000	250,000 €	11,061,394 €	2%

shadow price is set too low and only has an influence of 2–3 percent on the initial bid price$_{_n}$.

In order to encourage bidders to implement innovative sustainable projects, i.e., new, innovative construction methods/buildings, and to be able to reflect their environmental advantage over conventional applications in environmental terms, the PCC scenarios, i.e., the consideration of the GHG emissions bonus/malus, will be calculated for the final award decision, as follows:

$$\text{Bid price}_{PCC\_n}\ [€] = \text{Bid price}_{eCC\_n}\ [€] + \text{GHG emissions}_{BONUS/MALUS}[€]$$

where:

$$\text{GHG emissions}_{BONUS/MALUS}[€] = \left(GWP_{\_n}\ [t\ CO_2eq] - \frac{\sum_1^n GWP_{BIDDER}}{n} \right) \times RBCF_{carbon\ price}\ [€ / tCO_2eq]$$

Table 7 shows the calculation of the bid price$_{PCC_n}$ based on the LCA-based bonus/malus system. The bid price$_{PCC_n}$ is a fictitious price that is used for the final award decision. In the validation scenario 1, bidder 6 is awarded the contract.

Bidder 6 submitted a bid of € 9,433,273 during the bidding process. The difference between the bid price$_{_6}$ and the bid price$_{eCC_6}$ (bid price$_{_6}$

Table 7
Scenario 1: Bid price$_{PCC}$ with a shadow price and a RBCF carbon price of 400€/tCO_2eq, NFA 5,000 m², RSP 50 years.

	Bid price$_{eCC}$ [€]	GWP [tCO_2eq]	Deviation to GWP mean value [tCO_2eq/]	GHG emissions bonus/malus [€]	Bid price$_{PCC}$ [€]	Share GHG emissions bonus/malus/bid price [%]
Bid 1	12,710,041	5,750	464	185,714 €	12,895,755 €	1%
Bid 2	**11,420,200**	**6,000**	**714**	**285,714 €**	**11,305,914 €**	**3%**
Bid 3	12,033,478	6,500	1,214	485,714 €	12,519,192 €	4%
Bid 4	12,621,849	4,500	−786	−314,286 €	12,307,563 €	−2%
Bid 5	12,268,947	5,500	214	85,714 €	12,054,661 €	1%
Bid 6	**10,933,273**	**3,750**	**−1,536**	**−614,286 €**	**10,318,987 €**	**−6%**
Bid 7	12,811,394	5,000	−286	−114,286 €	12,397,108 €	−1%
		$\overline{X}$ = 5,286				

+ external cost $_6$) amounts to 1,500,000 € and must additionally be paid by the awarding authority to a public (construction) climate fund. The awarding authority will thus seek to lower the external cost, which can be achieved by GHG emissions reduction. As opposed to this the bidders will seek low carbon offers in order to maintain the competitive edge. The relevant control variable for these project-related GHG emissions penalties is the level of the shadow price.

Since bid 6 shows a reduction in GHG emissions in a relative comparison, i.e., based on the GWP mean value, with the other bids, bidder 6 receives a GHG emissions bonus on its bid price$_{eCC_6}$. Thus, the awarding authority has to award the contract to bidder 6 according to the lowest bid price$_{PCC_n}$ after the application of the LCA-based bonus/malus system. The initially submitted bid price $_6$ remains the basis for invoicing the construction work. The relative savings in external cost through GHG emissions bonus/malus € 614,286, e.g. as a result of innovative construction projects, are to be financed by a public (construction) climate fund. In this scenario, this means that the awarding authority pays an additional € 1,500,000 to the construction climate fund at the beginning and subsequently receives a return of € 614,286 due to the GHG emissions bonus. In this case the awarding authority must expect an additional cost of € 885,714 due to a future carbon pricing.

Assuming a shadow price of € 50/tCO_2eq (see Table 8), the bid order does not change due to external cost. In this case, the external cost due to the LCA-based bonus/malus system of bid 2 amount to € 35,714 €. In this case, the external cost of € 300,000 would be incurred in addition to the bid price $_2$ and would have to be paid to a public (construction) climate fund. Based on the GHG emissions malus, i.e., due to the comparatively higher GHG emissions of the bid, an additional amount, i.e., GHG emissions malus, of € 35,714 is prescribed to the awarding authority, which also has to be paid to the public (construction) climate fund.

The growing budget in the climate fund can be used to return money to the awarding authority through subsidies or to finance other climate-relevant projects. In the start-up phase, i.e., as long as the climate fund is not yet filled, a kind of start-up financing, through government subsidies, must be provided. The amount of funding from the construction climate fund and the amount of penalties to the construction climate fund can be controlled with the level of the RBCF carbon price. The shadow price and the RBCF carbon price do not have to be of the same level.

4.2. *Measures for the implementation of the LCA-based bonus/malus system*

The developed LCA-based bonus/malus system is made up of three sets of measures, which in turn consist of individual measures. These three sets of measures are (i) measures set for public procurement law, (ii) measures set for LCA methodology, and (iii) measures set for monetization.

The requirements of the legal implementation of LCA in the tendering and awarding processes and the awarding based on the application of the LCA-based bonus/malus system are described in the measures set under public procurement law. The definition of the calculation principles is described in the measures set for the LCA methodology. The procedure for the calculation of the external cost and the addition and deduction of the GHG emission bonus/malus to the bid price are described in the measures set for monetization. Table 9 shows the individual measures to be implemented in the conventional procurement processes.

Table 9
Measures for the implementation of the LCA-based bonus/malus system.

Set of measures	Individual measures
Measures set for public procurement law	Definition of the type of the applied performance specification Permission of alternative offers within tendering based on a constructive performance specification Definition of an appropriate GHG reference value depending on the functional equivalent as an environmental exclusion criterion Definition of the LCA-based bonus/malus system as cost model for the award criterion Definition of the applied carbon pricing instruments and their exact values (e.g., shadow price and results-based climate finance approach) Definition of required calculation principles
Measures set for LCA methodology	Definition of the applicable standards, i.e., ÖNORM EN 15978 and ÖNORM EN 15804 Definition of the applicable database (e.g., ökobau.dat database) Definition of applicable datasets (e.g., use of local data sets like Austrian energy mix, Austrian district heating mix) Declaration of considered life cycle modules according to ÖNORM EN 15804 Definition of calculation requirements for the individual life cycle modules definition of the replacement cycles based on service life catalogs definition of energy demand calculation (e.g., based on heating and cooling loads) definition of assumptions for end-of-life modules Definition of applicable service life catalogs Definition of reference study period (e.g., 50 years) Definition of the considered environmental indicator (e.g., GWP in tCO_2eq)
Measures set for monetization	Calculation of external cost based on GHG emissions and shadow price Calculation of the GHG emissions bonus/malus based on GHG emissions deviation from the GHG emissions mean value of all bids and results-based climate finance approach Internalization of external cost in the bid prices

5. Discussion

The aim of the proposed LCA-based bonus/malus system was to develop a step-by-step guideline, which allows the consideration of GHG emissions of buildings already in the tendering and awarding phase. The results show that an early assessment of GHG emissions is possible with

Table 8
Scenario 2: Bid price$_{PCC}$ with a shadow price and a RBCF carbon price of 50€/tCO_2eq, NFA 5,000 m^2, RSP 50 years.

	Bid price$_{eCC}$	GWP	Deviation to GWP mean value	GHG emissions bonus/malus	Bid price$_{PCC}$	Share GHG emissions bonus/malus/bid price
	[€]	[tCO_2-eq]	[tCO_2-eq/]	[€]	[€]	[%]
Bid 1	10,662.541 €	5,750	464	23,214 €	10,685,755 €	0%
Bid 2	**9,270,200 €**	**6,000**	**714**	**35,714 €**	**9,305,914 €**	**0%**
Bid 3	9,758,478 €	6,500	1,214	60,714 €	9,819,192 €	1%
Bid 4	11,046,849 €	4,500	−786	−39,286 €	11,007,563 €	0%
Bid 5	10,306,447 €	5,500	214	10,714 €	10,317,161 €	0%
Bid 6	**9,620,773 €**	**3,750**	**−1,536**	**−76,786 €**	**9,543,987 €**	**−1%**
Bid 7	11,023,894 €	5,000	−286	−14,286 €	11,009,608 €	0%
		$\overline{X} = 5,285,714$				

the LCA method if required in the tender documents. The barriers to the implementation of LCA in this early phase are shown in a systematic literature review on identifying obstacles to LCA implementation in buildings procurement processes (Scherz et al., 2022c) and can also be overcome for a practical implementation as proven in other studies (Marinelli and Antoniou, 2019; Metham et al., 2022). The preparation of the tender documents plays a decisive role in the evaluation of buildings GHG emissions in the tendering and awarding phase. In this context, particular attention must be paid to the award criteria. Furthermore, establishing a comprehensive definition of all calculation bases of the LCA as well as the carbon pricing instruments is another important step. Depending on the type of performance specification, alternative offers for the relevant components must be permitted for the constructive performance specification in order to be able to take into account the know-how of the bidders. The findings also show that the ranking of bidders can be influenced to different degrees based on the level of the carbon prices, i.e., shadow price and RBCF carbon price. However, there is currently no agreement among experts on how to determine the level of a shadow price, or other internal carbon prices, such as the RBCF carbon price. Assigning a specific value to internal carbon prices can be a complex task, since this depends on several factors of influence on the calculation. One approach for avoiding the need to determine carbon prices is to establish a defined carbon budget as a criterion for awarding contracts. However, this method presents two challenges. First, there are currently no carbon budget values available for individual building types in Austria. Second, the "carbon budgets" award criterion would need to be given appropriate weighting relative to the price. While some benchmarks for the $kgCO_2eq/m^2$ of building area exist in the literature, they are not aligned with the necessary climate target paths to meet our climate goals.

As shown in the validation example, carbon prices of 50€/tCO_2eq do not change the ranking, whereas a carbon prices of 400€/tCO_2eq puts the environmentally best bidder ahead of the initial cheapest bidder.

The handling and implementation of external cost supported via a construction climate fund should lead the awarding authority to reduce GHG emissions significantly. On the one hand in order to pay the lowest external cost induced by e.g. a low carbon construction (low external cost) and on the other hand, to achieve a relatively high return of the invested external cost (high GHG emissions bonus). In addition to the awarding authority, the bidders also strive to submit more environmental offers by reducing the GHG emissions of the offered buildings in order to stay competitive. Due to the decreasing carbon budget and the large share on GHG emissions of the construction industry, the developed LCA-based bonus/malus system represents a crucial step towards a net zero carbon-built environment. Looking at the validation example, a reduction of 9 $kgCO_2eq/m^2_{NFA}$ x a over the RSP of 50 years, i.e., due to the award to bidder 6 with 15 $kgCO_2eq/m^2_{NFA}$ x a instead of bidder 2 with 24 $kgCO_2eq/m^2_{NFA}$ x a, can be achieved. Taking into account the entire life cycle of the building and the NFA, this results in a savings potential of a 2,250 tCO_2eq. At this point, however, it must be mentioned that the defined values for the GHG emissions of the seven bidders are assumed values based on the DGNB building certification system. Therefore, it should be noted that the calculated reduction potential is not a representative value for the Austrian building sector. However, expressed in relative values, the application of the LCA-based bonus/malus system within the modeled validation example brings a GHG emissions saving of 38%. A saving of this magnitude is also in line with the calculated reduction potential in the study by Scherz et al. (2023), where the LCA-based bonus/malus system was tested by conducting a LCA and LCC using 37 building scenarios (Scherz et al., 2023).

In the context of emissions per square meter of floor area, the choice between gross floor area (GFA) and NFA affects the development of benchmarks (Prasad et al., 2022). Since NFA is used for benchmarking in the DGNB building certification system, NFA was also used as the reference area in our study. Additionally, the choice of the reference area, i.e., GFA or NFA, has an impact on the definition of the functional equivalent.

5.1. Limitations of the study

It must first be mentioned that the focus and intention of this article is not to analyze the method of LCA in detail nor to explain the calculation of GHG emissions. The assessment of GHG emissions and both its scope and the difficulties it involves are not described in this article. Therefore, in the modeled validation example, the GHG emissions in $kgCO_2eq/m^2_{NFA}$ x a are based on literature benchmarks (see Table 3) and are given for seven submitted bids. A detailed validation of the model using a case study based on specific LCA and LCC inventories can be found in Scherz et al. (2023) (Scherz et al., 2023).

Since the developed LCA-based bonus/malus system is based on the Austrian Federal Procurement Act, there is a further limitation regarding the current applicability of the model for private awarding authorities, as unlike public awarding authorities, these are not bound by the Federal Procurement Act. Another point to consider is that the external costs do not encompass all the environmental indicators. Rather, they only account for the GWP environmental indicator in t/CO_2eq, which is monetized with internal carbon prices. However, the theoretical framework of the LCA-based bonus/malus system is extensible to all other environmental indicators, provided that a value for monetization is also defined. Monetization values for other environmental indicators exist, for example in the study of De Nocker and Debacker (2018) (de Nocker and Debacker, 2018). In terms of public procurement law, this means that the tender documents must contain further information on additionally required environmental impacts and, if applicable, their calculation methods as well as their price for monetization.

In practice, numerous award criteria are already applied in addition to the price, such as shortening of the execution period, extension of the warranty period, apprenticeships and women's quota or professional experience of key personnel. The award criterion in this study is the lowest price including the considered GHG emissions in the form of external cost and the GHG emissions bonus/malus, i.e., the application of the proposed LCA-based bonus/malus system. The weighting within the award criterion is therefore 100% on the price, which already takes into account the environmental impact of the buildings. Therefore, this study does not propose weighting keys for award criteria or explain decision tools such as multi-criteria decision methods for supporting the award decision.

The generalization of the results from this study is limited to Austria. The general structure and calculation algorithm of the LCA-based bonus/malus system could, however, represent a workable building basis in the course of national adoptions. The differences in the tendering and awarding processes as well as national legislations would also need to be taken into consideration in such a procedure.

5.2. Outlook

The goal of future projects and studies is the practical application of the LCA-based bonus/malus system. In this context, we applied and further validated the proposed LCA-based bonus/malus system on a real case study (Scherz et al., 2023). Additionally, a cooperation with the City of Graz has already been established in this context, which allows an extensive query of environmental properties of a building by means of a form sheet already in the architectural competition (Scherz et al., 2022b). An implementation of the LCA-based bonus/malus system or parts of it in the OIB guidelines (especially in OIB guideline no. 7) would exploit further potential for GHG emissions reduction in buildings.

Further analyses are also necessary with regard to the level of the internal carbon prices in order to ensure a high contribution to the reduction of GHG emissions.

In the future, so-called carbon limits for certain building components or buildings, as already provided in the DGNB building certification system for the whole building, and the exclusion of bids exceeding these limits, i.e., a benchmark for GHG emissions, will further support and accelerate the implementation of a more environmentally favourable procurement process.

6. Conclusions

The objective of this study was to develop a cost model, i.e., the LCA-based bonus/malus system, for the public procurement of buildings and to provide a step-by-step guide for practical application, in order to further develop building tendering and awarding procedures to meet the requirements of a carbon-neutral environment.

The literature background shows that while numerous articles deal with sustainable procurement in the construction industry, the LCA method is at present scarcely applied at all in procurement processes for buildings. However, in order to reduce the GHG emissions caused by the construction industry, a mandatory integration of LCA into the procurement process is required. Approaches to integrate GHG emissions and LCA into public procurement need to be developed, re-examined, tested and above all, implemented as soon as possible in order to reduce GHG emissions from the construction industry and thereby reduce the impact of climate change, which is threatening humanity. One possible approach to integrating LCA of GHG emissions into public procurement is the proposed LCA-based bonus-malus system.

The results show that it is possible to conduct an LCA of tendered buildings and that it can be integrated as a monetary value in the submitted bid prices. Individual measures have to be implemented for achieving practical implementation of this, which can be divided into three distinct sets (i) measures set for public procurement law, (ii) measures set for LCA methodology, and (iii) measures set for monetization. In these measures, the prerequisites which have to be implemented by awarding authorities, bidders and external sustainability assessment experts are defined in order to enable an early assessment of the GHG emissions of buildings in the tendering and awarding phase.

Particular attention is paid to the level of the internal carbon prices set as a means of analyzing how strongly this influences the ranking of bidders. In this context, it has been shown that a low carbon price has no effect on bidder ranking and thus does not counteract the awarding based on the lowest price. In addition, the carbon price represents the decisive control instrument for the reduction of GHG emissions from buildings by determining the level of environmental damage cost.

The tender documents for the application of the developed LCA-based bonus/malus system, have to be prepared in detail. After the bids have been submitted, the LCA is validated by the awarding authority or consolidated external sustainability assessment experts and compared with the defined environmental minimum criterion. Bids that exceed this value are eliminated. External cost are added to the bid prices of the remaining bids based on the calculated GHG emissions and based on a defined shadow price. Finally, a GHG emissions bonus or malus is calculated based on the deviations from the GWP mean value of all valid bids, monetized with the RBCF carbon price and added to or subtracted from the bid price. The results show that the level of the defined carbon prices can change the bid order and is therefore stated to be the most sensitive parameter.

With the application of the LCA-based bonus-malus system, competition can be stimulated in the direction of a more environmentally friendly competition and thus additional cost for more environmentally friendly construction methods can be compensated by GHG emission reductions, i.e., by saving external cost and generating a high GHG emissions bonus. GHG emissions can be reduced and thus progressive climate change can be combated by applying the suggested cost model. The practical implementation of both the LCA-based bonus/malus system and other innovative approaches, however, is mainly in the hands of policy makers, legislators and the awarding authorities.

Author contributions

Conceptualization, M.S.; methodology, M.S. and H.K.; validation, M. S., H.K. and A.P.; formal analysis, M.S.; investigation, M.S.; resources, M.S.; data curation, M.S.; writing—original draft preparation, M.S.; writing—review and editing, M.S., H.K. and A.P.; visualization, M.S.; supervision, H.K. and A.P; project administration, H.K and A.P.; All authors have read and agreed to the published version of the manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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Thesis publication 3

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BUILDING COMPONENTS AND BUILDINGS

Strategies to improve building environmental and economic performance: an exploratory study on 37 residential building scenarios

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Abstract

Purpose With a contribution of 39% to greenhouse gas (GHG) emissions, reducing the environmental impacts of buildings plays an undisputed role in achieving climate goals. Therefore, the development of projects with a low carbon footprint is of crucial importance. Although several active and passive solutions as well as design strategies have been developed, identifying critical levers to minimise GHG emissions and the cost of future building projects is still a problem faced every day by designers.

Methods Motivated by this knowledge gap in this study, we conducted a life cycle assessment (LCA) and life cycle cost analysis (LCCA) of a residential building situated in Austria. To identify the critical levers for reducing impacts and cost, 37 scenarios with three different advanced energetic standards are created. The scenarios with the various standards are developed through the combination of different construction materials, insulation materials and technical building equipment. In the eco-efficiency assessment (LCA and LCCA), a reference study period of 50 years is assumed. The life cycle of the building scenarios was analysed according to the European standard EN-15978.

Results Results show that improving the energetic standard does not yield an overall cost savings potential. The additional construction cost (23%) for energy efficiency measures, including thermal insulation and change of technical building equipment, is higher than the reduction potential in operating cost over 50 years. On the other hand, the improvement of energetic standards allows a reduction of the environmental impacts by 25%.

Conclusions To ensure a cost-optimal environmental improvement of buildings, it is crucial to conduct an eco-efficiency assessment during the design process of energy-efficient buildings. This study shows how improving the energetic standard of buildings can reduce environmental impacts with slightly increased life cycle cost.

Keywords Life cycle assessment, Life cycle cost analysis · Building optimisation · Sustainable construction

1 Introduction

According to the Intergovernmental Panel on Climate Change's (IPCC) scenarios, the rate of greenhouse gas (GHG) emissions will double by 2030 unless urgent action is taken. This increase in emissions will have catastrophic consequences for many species and the world economy (UNEP 2009). To prevent climate change by limiting global

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Highlights
- Improved energetic standards lead to decreased operational impacts.
- Embodied impacts differ significantly only between the 'low-energy' and 'passive house' standards.
- Maintaining higher energetic standards results in slightly higher construction cost.
- The 'low-energy' standard shows similar life cycle cost analyses results as the 'passive house' standard.

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warming to 1.5 °C, with their ratification of the Paris Agreement, 197 countries indicated their commitment to achieving at least an 80% reduction in global emissions by the year 2050 (UNEP 2015). Worldwide, the building sector is considered to be responsible for 39% of GHG emissions (UNEP 2019), which makes it the biggest field of action. To actively effect changes, scientists have sought solutions either for upstream (material/systems) or for downstream (operational energy) building life cycle stages for more than 30 years.

Two groups of solutions are provided for the reduction of the environmental impacts of the operational stage. The first improves the carbon content of the energy source while the second minimises the required amount of energy. Within the building context, several national and international strategies (Myhrvold and Caldeira 2012) using renewable energy sources that lower the carbon content of the electricity grid have been analysed and proposed. Such solutions promise to reduce both operational and embodied impacts (Alig et al. 2020). The second solution contains active and passive solutions, enabling the improvement of energy efficiency of buildings for heating, cooling, ventilation or technologies producing low-carbon electricity. The application of these active and passive strategies has allowed the development of construction projects with different energy labels regarding consumption (Lasvaux et al. 2017; Drouilles et al. 2019). To reflect the energetic efficiency of building projects, various advanced standards (low-energy house, passive house or plus-energy house) have been introduced. The requirements for energetic standards are defined in the European Energy Performance of Buildings Directive (EPBD) (European Commission 2010). In Austria, these requirements have been transposed into national law through the Austrian Building Code Directive (Österreichisches Institut für Bautechnik 2015).

On the other hand, a recent study carried out to analyse 656 building case studies showed that a significant shift of impacts occurred from the operational stage to the building fabric and its equipment (Röck et al. 2020). Nevertheless, a clear trend is emerging. More investments are being made in the design of more energy-effective buildings, and more attention is being paid to the embodied energy and the related embodied impacts of building concepts, considering the whole life cycle (e.g. the activities of IEA EBC Annex 57 and IEA EBC Annex 72). John and Habert (2013) presented the environmental impacts of 12 buildings situated in Switzerland. They identified the components with larger contribution to buildings' environmental impacts. In the case of new and retrofitting scenarios, Hollberg and Ruth (2016) proposed a parametric approach enabling the minimisation of the embodied impacts of building projects. The novel approach reduced the effort of performing life cycle assessment (LCA) and guided architects towards low carbon projects. Considering both operational and embodied impacts, by varying design parameters and implementation of different passive and active strategies, Jusselme et al. (2016) and Drouilles et al. (2019) identified the most environmentally friendly solutions for the Swiss context. In the study presented by Allacker and De Troyer (2013), optimisation solutions from a life cycle environmental impact and cost perspective were analysed and identified. In the context of eco-efficiency assessment, Galimshina et al. (2021) investigated climate-friendly and cost-effective renovation scenarios for building renovation scenarios by using LCA and LCCA. After using the multi-objective optimisation approach, the study showed that the replacement of the heating system plays a crucial role in the reduction of environmental impacts. A further study applied many-objective optimisation to identify good energy-environment cost renovation solutions. By analysing the Pareto-optimal solutions, refurbishment actions have been identified (Pannier et al. 2019).

However, the literature lacks studies analysing the correlation between embodied and operational impacts through the improvement of the energetic standard in a single case study for the Austrian context.

Furthermore, in the existing LCA literature about buildings, few evaluations are found of different energetic standards and the influence of technical building equipment and/or different building materials (Hoxha et al. 2017). Besides, previous studies have not analysed the correlation between environmental and economic performance in a large number of new constructed building case studies in order to identify actions that can be taken to optimise buildings or their materials to reduce energy consumption and emission.

In our study, we assessed the environmental impacts of 37 building scenarios with different energetic standards. The study also addresses the influence of the energetic standard, the construction material, the insulation material and the technical building equipment on the impact on the environmental and economic performance of the case study building. In this context, the following study aims:

- to highlight the ratio of embodied and operational environmental impacts;
- to highlight the ratio of construction cost and operational cost;
- to identify the scenario with the lowest environmental impacts and lowest life cycle cost;
- and to highlight the correlation between environmental impacts and life cycle cost.

2 Methods

The method applied in this study follows the three steps: (i) definition of case study, (ii) LCA and LCCA, and (iii) critical interpretation of results. In the first step, 37 building scenarios with different energetic standards are developed. Then the environmental impacts and life cycle cost of all scenarios are calculated, and finally the results are analysed with the help of the statistical two-sample *t* test.

2.1 Case study

The case study described in this paper represents a two-storey residential building situated in Austria. Based on the architectural design of the building (Fig. 1), three distinct advanced energetic standard scenarios, (i) 'low-energy', (ii) 'passive house' and (iii) 'plus-energy', are defined, based on a heat-demand perspective that is in accordance with Austrian Standards (Austrian Standard Institute 2011b), The 'low-energy' standard represents the lowest energetic standard addressed, with a heating energy demand of about 40 kWh/m^2_{NFA}/year. The considered 'passive house' standard has a heating energy demand of 10 kWh/m^2_{NFA}/year. The 'plus-energy' standard also requires about 10 kWh/m^2_{NFA}/year, but this energetic standard is assumed to be equipped with 61-m^2 photovoltaic (PV) panels, which produce additional electricity. This generated electricity is only used for self-consumption and was subtracted from the total electricity consumption of the case study. The additionally generated benefit of PV electricity production, e.g. as grid feed-in, is not considered and therefore does not yield any benefit in further calculations.

Based on these three energetic standards, we generated different scenarios by varying the construction material, thermal insulations and technical building equipment (Mötzl 2014; Sölkner et al. 2014; Passer et al. 2016). By applying this approach, a total of 37 scenarios are defined, each fulfilling its respective requirement to meet the respective energetic standard. With a gross floor area (GFA) of 220 m^2 (ground floor and first floor), this building is analysed for a reference study period of 50 years. The selected building scenarios were calculated using the calculation method defined in the energy performance regulation in Austria, and their structures were dimensioned to achieve a consistent heating demand. In all generated scenarios, the outer dimension is not modified and, therefore, only the net floor area (NFA) varies due to modified thicknesses of the construction material and the insulations. This requirement was given due to the Austrian

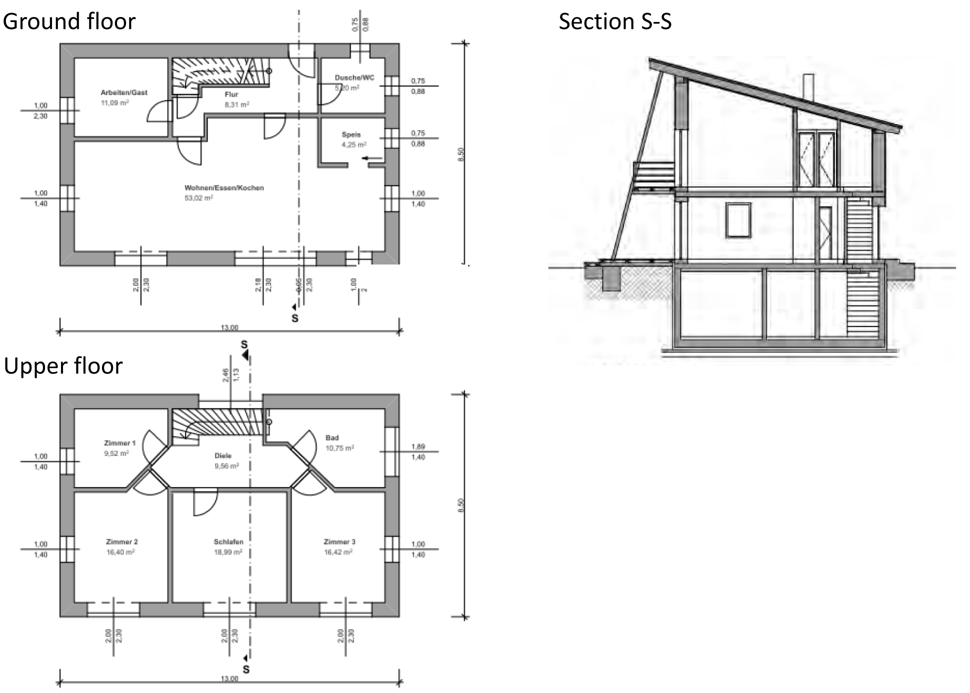

Fig. 1 Floor plans and cross section of the two-storey residential building

building specifications, as it is not always possible to change the outer dimensions of buildings. Furthermore, the parameters of the cellar (built with reinforced concrete) are also kept the same for each scenario.

To ensure that the 37 scenarios developed can be clearly identified, different codes are assigned. These codes consist of a sequence of four letters as shown in Fig. 2. The first letter differentiates the scenarios according to their energetic standard. The three energetic standards are the 'low-energy' standard, the 'passive house' standard and the 'plus-energy' standard with the abbreviations L, P and PE. The second letter indicates the construction material used (codes B, C, Wc, W_f and Ws). The subscript for this letter gives additional information about the thickness (in centimetres) of the construction material. The third defines the insulation materials used (codes E, R, W_f and 0). The subscript for this letter gives additional information about the thickness (in centimetres) of the insulation material. The fourth letter indicates the technical building equipment implemented in the 37 different scenarios. The technical building equipment includes heat pumps based on groundwater and on air-air compact unit and pellet boilers (codes H_{GW}, H_{CU} and P). In the supplementary material, we summarise detailed information about the 37 generated scenarios. In order to achieve the 'low-energy' standard in the scenarios without thermal insulation, either bricks with integrated thermal insulation or bricks with a thickness of 50 cm were used.

2.2 Environmental and economic performance of buildings

Based on the prepared plan documents for each construction method and their energetic standards, a construction company drew up service specifications for the buildings, including quantities and unit prices. The construction cost of the individual buildings were calculated by a general contractor, and the bills of quantities were made available for further calculations of the environmental and economic performance of the buildings. All costs for the construction of the building scenarios were calculated by the construction company, and no other literature benchmarks were used. Service life catalogues were used to determine the replacement cycles of materials and components. The electricity price and the pellet price at the time of the study were used to calculate the operational cost.

In the eco-efficiency assessment (LCA and LCCA), a reference study period of 50 years is assumed.

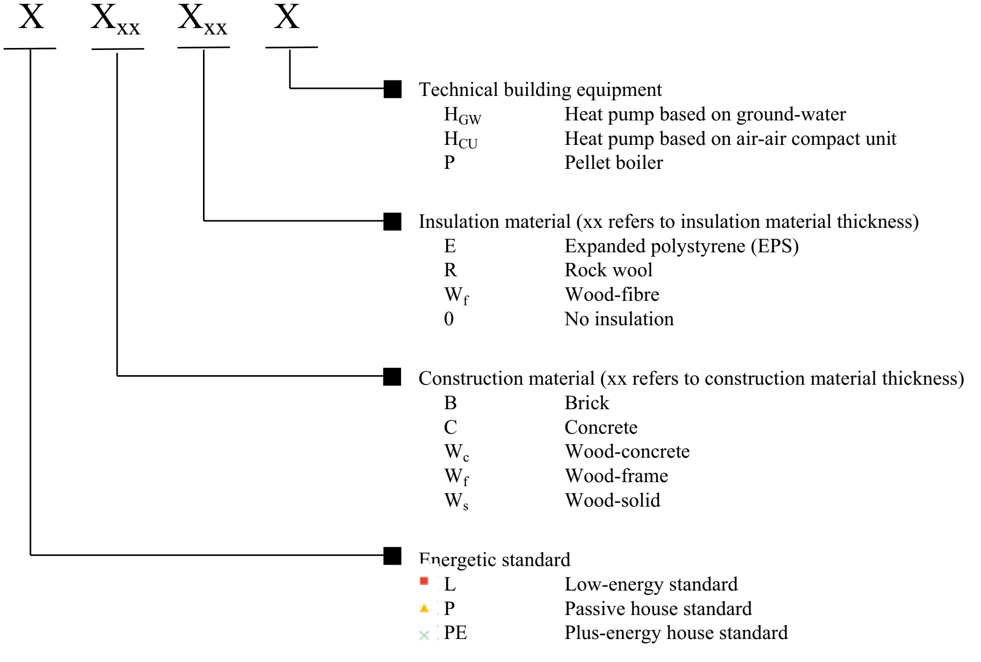

Fig. 2 Codes for the generated scenarios (energetic standard, construction material, insulation material and technical building equipment)

The life cycle of the building scenarios was analysed according to the European standard EN-15978 (CEN/TC 350 2011). This standard breaks down the impacts according to building life cycle stages: product stage (A1–A3), construction process stage (A4–A5), use stage (B1–B6), end-of-life stage (C1–C4) and benefits and loads beyond the life cycle (D).

The LCA includes the operational as well as embodied impacts. Embodied impacts are calculated by examining the construction materials as well as the technical building equipment. The system boundaries are limited to the life cycle stages of the production stage (A1–A3), construction process stage (A4–A5) replacement (B4), operational energy use (B6), demolition (C1), transport (C2), waste processing (C3) and disposal (C4). The impacts of the production stage (A1–A3) and the observed end-of-life modules (C3, C4) are based on the quantities of materials described in the bills of quantities. The environmental impacts of modules A5 and C1 were considered as ratio respectively equal to 5% and 2% of the impact of the product stage (A1–A3) (Hoxha et al. 2016; Lützkendorf et al. 2014). Simplification in assessing the environmental impacts of these stages is due to the lack of data on construction and demolition processes defined per construction type. Furthermore, the impacts of these stages are considered as ratio to also consider the influence of technical building equipment for which there is a lack of information in the literature (Hoxha et al. 2017). The replacement of the building components and materials during its reference study period (B4) are defined based on service life data for building components (Landesverband Steiermark und Kärnten 2020). The impact of the operational stage (B6) for heating, cooling, ventilation, hot water, lighting and appliances is calculated according to Austrian requirements for energy certificates of buildings (Österreichisches Institut für Bautechik 2015) and the Austrian electricity mix. The Swiss Ecoinvent database v.3.6 (Wernet et al. 2016) is used to calculate the environmental indicator of the global warming potential (GWP). The life cycle inventory of 37 building scenarios, hypothesis and the unit process considered in the calculation are provided in the supplementary material. Considering the system model 'Allocation, recycled content', which is also referred to as the 'cut-off approach,' the GWP indicator is calculated using the IPCC impact assessment method (Stocker et al. 2014). The calculation of the environmental impacts of all building scenarios is conducted in the LCA software SimaPro (Pré Consultants 2018). The environmental impacts are assessed on the basis of the defined functional unit as square metre net floor area (NFA) over the defined reference study period ($m^2{}_{NFA}$).

The life cycle cost analysis (LCCA) can be carried out for the entire building or for individual building components (structural elements, individual building component layers or technical building equipment). The framework for the evaluation of the economic performance of buildings is specified at the European level in EN 16,627:2015 (CEN/TC 350 2015). LCCA takes into account cost components such as construction cost (e.g. professional fees, temporary work, construction of asset), operational cost (e.g. rent, cyclical regulatory cost, utilities), maintenance cost (e.g. maintenance management, repairs and replacement of minor components, replacement of major systems and components, cleaning) and end-of-life cost (e.g. disposal inspections, disposal and demolition).

In this study, the net present cost method is applied in order to compare the economic performance for the scenarios of the two-storey building (Schulte 2015, Nwogug 2016). Based on the service specifications, the construction cost (A1–A3) is calculated in accordance with ÖNORM B 1801–1 and ÖNORM B 1801–2 (Austrian Standard Institute 2009, Austrian Standard Institute 2011a). To ensure comparability between construction cost and embodied impacts, the costs of the replacement of building components as part of the maintenance cost are added to construction cost. The costs of the replacement of building components are based on service life data for building components (Landesverband Steiermark und Kärnten 2020). The operational costs (B6) are based on the defined electricity price (0.17 €/kWh), the defined pellet price (0.25 €/kg) and the different heating demand of the different energetic standards (Eurostat 2020; proPellets Austria 2022). Additional calculation parameters for the dynamic LCCA (discount rate = 5.5%, inflation rate = 2.0%, escalation rate (energy) = 4.0%, and escalation rate (construction services) = 2.0%) are based on the building certification standard of Austrian sustainable building council. For a more detailed analysis we are not applying the average inflation rate for all goods and services. However, we considered the specific escalation rate for construction services and energy. The average inflation rate is used to calculate the real discount rate. In the LCCA, the end-of-life stage (C1–C4) is not considered. The calculated costs of the scenarios are expressed in life cycle cost (€/$m^2{}_{NFA}$ net).

2.3 Critical interpretation

To strengthen the comparison between two series of data, the statistical two-sample *t* test is found useful. Within the study, there are the following three series of data: (i) low-energy standard buildings with 16 scenarios, (ii) passive house standard buildings with 14 scenarios and (iii) plus-energy house standard buildings with 7 scenarios.

Within the objective of this study, the test is used to compare the environmental impacts of the building scenarios with different energetic standards. The defined null hypothesis (H_0) is tendentially that no difference exists between the means of the two populations:

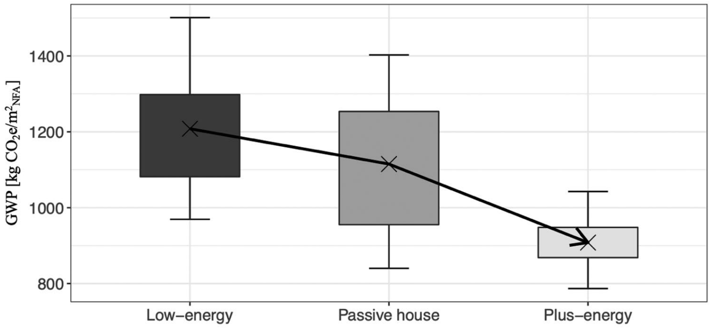

Fig. 3 Life cycle global warming potential (GWP) of building scenarios, clustered by their energetic standards

$$H_0 : \mu_1 - \mu_2 = 0 \tag{1}$$

where μ_1 and μ_2 present the mean values of the first and second series of data.

The t value is calculated with the equation:

$$t = \frac{\mu_1 - \mu_2}{\sqrt{\frac{\sigma_1^2}{n_1} + \frac{\sigma_2^2}{n_2}}} \tag{2}$$

where σ_1^2 and σ_2^2 present the variances, and n_1 and n_2 the number of samples.

The threshold t_{crit} for rejecting or accepting the null hypothesis is calculated using the equation:

$$t_{crit} = (1 - \frac{1}{2} * \alpha, n_1 + n_2 - 2) \tag{3}$$

where α represents the level of significance.

For $\alpha = 0.05$, the t value calculated with Eq. (2) is compared with the t_{crit} from t distribution tables. If $t < t_{crit}$, then no significant difference between the two groups of building scenarios is observable, otherwise a significant difference is observable.

3 Results

3.1 Environmental impacts

Figure 3 shows the results of the LCA of the global warming potential (GWP) indicator for 37 scenarios, clustered by their energetic standards. For the 'low-energy' standard, the scenarios have an average impact of 1208.1 $kgCO_2e/m^2_{NFA}$. An increase in the energetic standard to that of the 'passive house' standard brings an average reduction in impact of 93.1 $kgCO_2e/m^2_{NFA}$. By improving the standard further to the 'plus-energy' standard, we observe an average reduction of 300.0 $kgCO_2e/m^2_{NFA}$ compared with the 'low-energy' standard. The impact reduction between the 'passive house' standard and 'plus-energy' standard is 206.9 $kgCO_2e/m^2_{NFA}$. To increase the robustness of the comparison of results, the analyses should be carried out taking into account the intervals between the values, so that a statistical test is required. For this purpose, a two-sample t test is performed to assess the statistical differences between the results.

A significance level of 5% (α=0.05) is chosen, which means that the difference of the compared mean values is significant if the p value in the test falls below 0.05. In Table 1, the calculated p values are shown. The results of the t tests show that the differences among the analysed mean values between the 'low-energy' and 'plus-energy' standards, as well as the differences between the 'passive house' and the 'plus-energy' standards, are significant. In contrast, the p value for the difference in the mean values between the 'low-energy' and 'passive house' standards falls below the chosen significance level of 5% (α=0.05). Consequently, the environmental impact differences between the scenarios of the 'low-energy' and 'passive house' standards are not significant.

3.2 Differentiation between embodied and operational impacts

To identify the contributors to the GWP indicator, a distinction must be made between embodied and operational impacts. Figures 4 and 5 show the distribution of

Table 1 Independent t test for the comparison of GWP (total impacts) reduction potential

Comparison between			P value	Significance
Low-energy standard	and	Passive house standard	0.060	No
Passive house standard	and	Plus-energy standard	0.004	Yes
Low-energy standard	and	Plus-energy standard	0.000	Yes

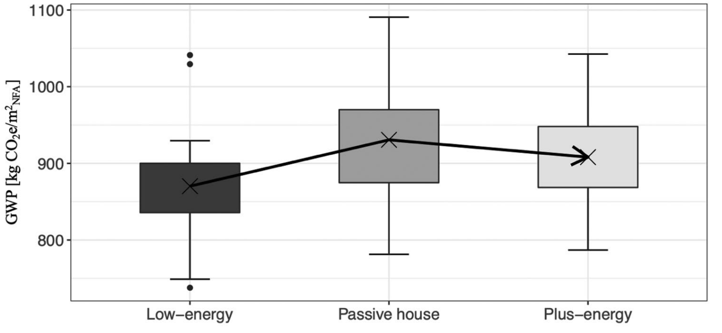

Fig. 4 Variations among embodied impacts

the environmental impacts of GWP in terms of embodied impacts and operational impacts for the 37 scenarios, clustered according to their energetic standards.

The results for the embodied impacts show that there is an increase in impacts between ‘low-energy’ and ‘passive house’ standards in an amount of 60.5 $kgCO_2e/m^2_{NFA}$ and a decrease in embodied impacts between ‘passive house’ and ‘plus-energy’ standards in an amount of 22.6 $kgCO_2e/m^2_{NFA}$.

The statement that a reduction of embodied impacts occurs between ‘passive house’ standard and ‘plus-energy’ standard cannot be generalised, but results from the composition of the scenarios. In addition, among the seven ‘plus-energy’ standard scenarios, there are four scenarios with wooden construction materials, namely Ws_{40}-R_{40}-Hcu, Wf_{40}-R_{40}-Hcu, Wc_{18}-E_{26}-Hcu and $Wc_{36,5}$-E_{11}-Hcu, which also leads to this reduction. Furthermore, it should be mentioned that the *t* test classifies the comparison of these two energy standards as not significant based on the selected scenarios.

The increase between ‘low-energy’ and ‘plus-energy’ standards is 37.9 $kgCO_2e/m^2_{NFA}$.

For the ‘low-energy’ standard, four outliers can be identified. Of these, two are below the boxplot antennas (the second one is not visible in Fig. 4, because the values are almost identical) and two are above the boxplot antennas. The scenarios with the lowest embodied impacts are scenarios Wf_{26}-R_{26}-P and Wf_{26}-R_{26}-Hgw. These two scenarios have the lowest embodied impacts because the construction material is wood with a thickness of 26 cm. Regarding the embodied impacts, the installed rock wool insulation does not worsen the ranking of these two scenarios compared to the other 35 scenarios. The scenarios with the highest embodied impacts are scenarios B_{50}-0-P and B_{50}-0-Hgw. Despite the absence of thermal insulation in these two scenarios, they have the highest embodied impacts. This is due to the fact that a 50-cm-thick brick (including the required cement mortar) was used to achieve the ‘low-energy’ standard requirements.

The reduction of embodied impacts between ‘passive house’ and ‘plus-energy’ standard requires more detailed consideration. In terms of embodied impacts, the ‘passive house’ standard scenarios with the heat pump are on average slightly below the average embodied impacts of the ‘plus-energy’ standard scenarios, while the ‘passive house’ standard scenarios with the pellet heating system are on average slightly above the ‘plus-energy’ standard scenarios.

The *t* test results in Table 2 show insignificant differences regarding the embodied impacts between the ‘passive

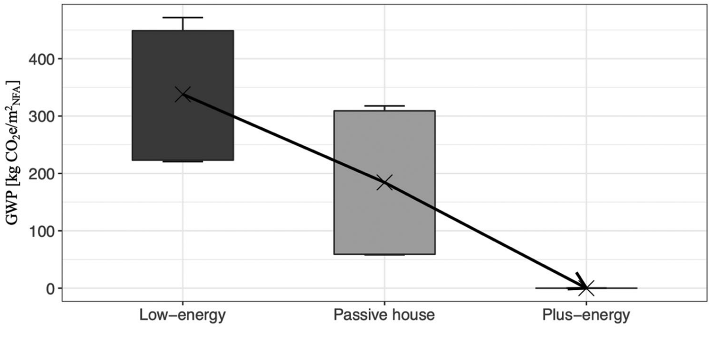

Fig. 5 Variations among operational impacts

Table 2 Independent *t* test for the comparison of GWP (embodied impacts) reduction potential

Comparison between			*p* value	Significance
Low-energy standard	and	Passive house standard	0.028	Yes
Passive house standard	and	Plus-energy standard	0.282	No
Low-energy standard	and	Plus-energy standard	0.160	No

Table 3 Independent *t* test for the comparison of GWP (operational impacts) reduction potential

Comparison between			*p* value	Significance
Low-energy standard	and	Passive house standard	0.001	Yes
Passive house standard	and	Plus-energy standard	0.000	Yes
Low-energy standard	and	Plus-energy standard	0.000	Yes

house' standard and the 'plus-energy' standard and between the 'low-energy' standard and 'plus-energy' standard. From the results of the *t* test, it can be concluded that the chosen building materials for the investigated two-storey residential building only have a significant influence on the difference of the embodied impacts between the 'low-energy' standard and the 'passive' standard. Due to the insignificant differences between the 'passive house' standard and the 'plus-energy' standard, the change in total impacts over the whole life cycle, therefore, can be explained by examining the reduction in operational impacts for each of the individual energetic standards.

The results for the operational impacts show that there is a decrease in impacts between 'low-energy' and 'passive house' standards in an amount of 153.6 $kgCO_2e/m^2_{NFA}$ and a decrease in operational impacts between 'passive house' and 'plus-energy' standards in an amount of 184.3 $kgCO_2e/m^2_{NFA}$. The decrease between 'low-energy' and 'plus-energy' standards is 337.9 $kgCO_2e/m^2_{NFA}$.

The 'plus-energy' standard is equipped with an energy supply concept that pursues a similar goal as a zero-energy house, but in this case the annual energy balance is positive. Within the scope of the study, the energy demand for heating and cooling and the energy demand for ventilation were taken into account. Within the 'plus-energy' standard scenarios, this total electricity consumption is completely covered by the PV electricity production. The energy demand for lighting, household electricity or electric charging infrastructure for mobility needs was not taken into account.

The *t* test results highlighted in Table 3 show significant differences regarding the operational impacts between all considered energetic standards.

3.3 Life cycle cost

In Fig. 6, we show the life cycle cost of the 37 scenarios, clustered by their energetic standards. The scenarios with a 'low-energy' standard have an average life cycle cost of 2562 €/m^2_{NFA}. The adjustment of the energetic standard to that of 'passive house' standard leads to an average increase in the life cycle cost of approximately 251 €/m^2_{NFA}. An increase from the 'low-energy' standard to the 'plus-energy' standard leads to an additional life cycle cost of approximately 396 €/m^2_{NFA}. The increment in life cycle cost observed when the energetic performance of buildings is improved from 'passive house' to 'plus-energy' standard is 145 €/m^2_{NFA}. In terms of life cycle cost, the results also show an outlier for the 'plus-energy' standard. The solid wood construction (Ws) with 40 cm

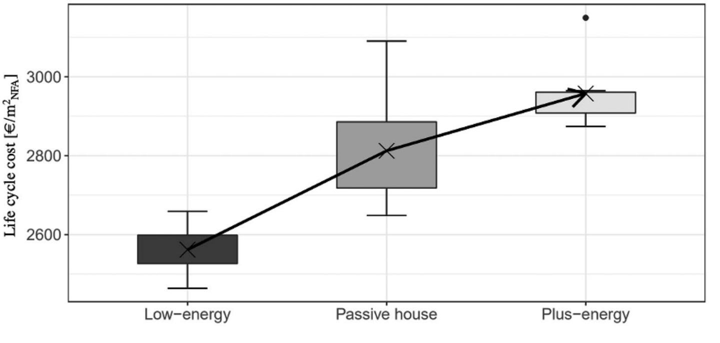

Fig. 6 Average life cycle cost of building scenarios, clustered to their energetic standards

Table 4 Independent *t* test for the comparison of life cycle cost

Comparison between			*p* value	Significance
Low-energy standard	and	Passive house standard	0.000	Yes
Passive house standard	and	Plus-energy standard	0.006	Yes
Low-energy standard	and	Plus-energy standard	0.000	Yes

mineral wool thermal insulation is 3150 €/m$^2_{NFA}$. This outlier is due to the high construction cost of the 40-cm-thick solid wood construction and the additional mineral wool insulation.

The *t* test results for the comparison of life cycle cost between scenarios with different energetic standards are presented in Table 4. The comparisons between the considered energetic standards show significant differences in terms of the calculated average of the building scenarios within a chosen significance level 5% ($\alpha = 0.05$).

3.4 Differentiation between construction cost and operational cost

Figures 7 and 8 show the distribution of the construction and operational cost for the 37 scenarios, clustered according to their energetic standards. Unlike the distribution of environmental impacts, the construction cost differs in a broader range within the individual energetic standards. It has to be mentioned that the cost of the replacement of building components as part of the maintenance cost has been added to the construction cost in order to compare them with the results of the embodied impacts.

The results for the construction cost show that there is an increase in cost between 'low-energy' and 'passive house' standards in an amount of 291 €/m$^2_{NFA}$ and a further increase in construction cost between 'passive house' and 'plus-energy' standards in an amount of 256 €/m$^2_{NFA}$. The increase between 'low-energy' and 'plus-energy' standards is 547 €/m$^2_{NFA}$. The solid wood construction is again an outlier, mainly due to the construction cost. These, like the total life cycle cost, amount to 3150 €/m$^2_{NFA}$, since the operational cost in the 'plus-energy' standard scenarios is equal to zero. This high construction cost in scenario Ws_{40}-R_{40}-Hcu in the 'plus-energy' standards arises from the solid wood construction with a thickness of 40 cm. This result is also evident in scenario Ws_{40}-R_{40}-Hcu in the 'passive house' standards. The higher construction cost of the 'plus-energy' standard scenario Ws_{40}-R_{40}-Hcu compared to the same constructive scenario Ws_{40}-R_{40}-Hcu in the 'passive house' standard can be explained by the increased technical building equipment requirements.

The *t* test results for the comparison of construction cost between scenarios with different energetic performance are presented in Table 5. The comparisons between the considered energetic standards show significant differences in terms of the calculated average of the building scenarios within a chosen significance level 5% ($\alpha = 0.05$).

The results for the operational cost show that there is a decrease between 'low-energy' and 'passive house' standards in an amount of 41 €/m$^2_{NFA}$ and a decrease between 'passive house' and 'plus-energy' standards in an amount of 110 €/m$^2_{NFA}$. The decrease between 'low-energy' and 'plus-energy' standards is 151 €/m$^2_{NFA}$. The operational cost for the scenarios of the 'plus-energy' buildings is equal to zero because the net electricity consumption after subtracting the PV electricity production is zero. Furthermore, no benefit is attributed due to the potential overproduction.

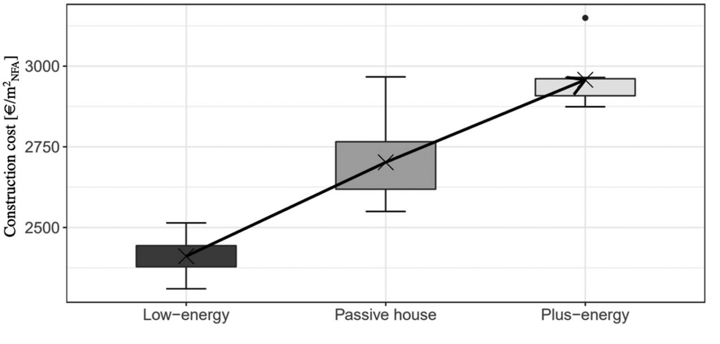

Fig. 7 Variations among construction cost (incl. replacement cost) for scenarios with different energetic standards

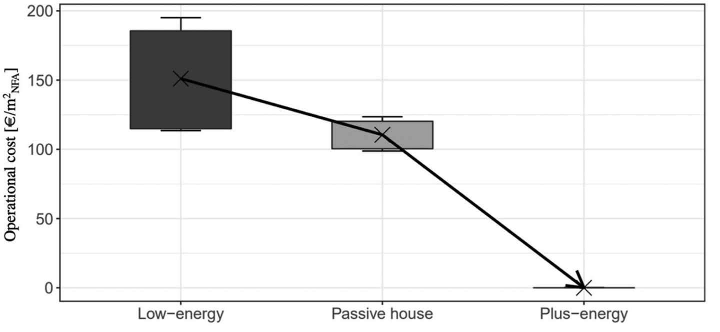

Fig. 8 Variations among operational cost for scenarios with different energetic standards

Table 5 Independent *t* test for the comparison of construction cost (incl. replacement cost) reduction potential

Comparison between			*p* value	Significance
Low-energy standard	and	Passive house standard	0.000	Yes
Passive house standard	and	Plus-energy standard	0.000	Yes
Low-energy standard	and	Plus-energy standard	0.000	Yes

The *t* test results for the comparison of operational cost between scenarios with different energetic performance are presented in Table 6. The comparisons between the considered energetic standards show significant differences in terms of the calculated average of the building scenarios within a chosen significance level 5% ($\alpha = 0.05$).

3.5 Change in construction cost to reduce GWP impacts of buildings

The relative influence of energetic standard improvement to overall impacts and cost is summarised in Table 7, where the 'low-energy' standard was assumed as equal to 100%. The most significant reduction potential can be achieved by increasing the energetic performance so that the 'low-energy' building meets the 'plus-energy' standard, but, on the other hand, this results in increased construction cost for the building project. The percentage comparison shows that this improvement in the energetic standard results in a 24.8% reduction in impacts, while an additional investment cost of 22.7% can be expected. The adaptation of the energetic standard to that of the 'passive house' standard leads to a reduction in the impacts by an average of 93 $kgCO_2e/m^2_{NFA}$ but causes an additional construction cost of 291 €/m^2_{NFA}. Measured in relative values, this translates to a 7.7% reduction in impacts with an additional construction cost of 12.1%. By improving the 'passive house' parameters to meet the 'plus-energy' standard, the additional construction cost amounts to 256 €/m^2_{NFA} and reduces the GWP indicator by 207 $kgCO_2e/m^2_{NFA}$. The percentage comparison indicates that this improvement in the energetic standard allows us to reduce the impacts by 17.1%, while an additional construction cost of 10.6% is predicted.

Finally, the results illustrate that an increase from a 'passive house' to a 'plus-energy' standard significantly reduced impact at a relatively low additional construction cost.

3.6 Clustering analysis

In order to compare the additional life cycle cost for the reduction of GWP indicator more effectively, we conducted a detailed investigation of the single scenarios. Figure 9 shows the 37 scenarios on a cost-environmental impact diagram. The *x* axis shows

Table 6 Independent *t* test for the comparison of operational cost reduction potential

Comparison between			*p* value	Significance
Low-energy standard	and	Passive house standard	0.000	Yes
Passive house standard	and	Plus-energy standard	0.000	Yes
Low-energy standard	and	Plus-energy standard	0.000	Yes

Table 7 GWP reduction potential compared to construction cost for different energetic standards over a reference study period of 50 years

		Low-energy standard		Passive-house standard		Plus-energy standard	
		GW reduction potential*	Construction cost**	GW reduction potential*	Construction cost**	GW reduction potential*	Construction cost**
Relative value output	Low-energy standard			−93 (−7.7%)	+291 (+12.1%)	−300 (−24.8%)	+547 (+22.7%)
	Passive-house standard	+93 (+7.7%)	−291 (−12.1%)			−207 (−17.1%)	+256 (+10.6%)
	Plus-energy standard	+300 (+24.8%)	−547 (−22.7%)	+207 (+17.1%)	−256 (−10.6%)		

*in kg CO_2e/m^2 NFA.

**in €/m^2 NFA.

the environmental impacts for the GWP indicator in $kgCO_2e/m^2_{NFA}$, and the *y* axis shows the LCC results in €/m^2_{NFA}.

It can be observed that scenarios with installed heat pumps (Hcu, Hgw) show lower impacts for all used construction materials. Looking more closely at the scenarios with heat pumps, it can be seen that those scenarios with wood construction (Wf, Wc and Ws) have lower impacts than the scenarios with other construction materials. On the other hand, the scenarios with the construction material brick (B) are the ones with higher environmental impacts.

Regarding insulation materials, the scenarios without insulation materials do not fall into the low environmental impact range due to weak performance during the building's use phase. No clear statement can be derived for the other insulation materials used.

Examining the scenarios from an economic perspective, the construction materials solid wood (Ws) can be classified as LCC driver. However, the other construction materials (Wf, C, B and Wc) and the insulation materials (R, E, Wf, 0) cannot be classified as LCC drivers. Regarding the technical building equipment, the heat pumps with groundwater (Hgw) scenarios incur the lowest life cycle cost. Scenarios with heat pumps with air-air compact units (Hcu), on the other hand, are in the upper cost range. Scenarios with pellet heating systems can be placed between these two ranges. In summary, for the considered reference study period and the

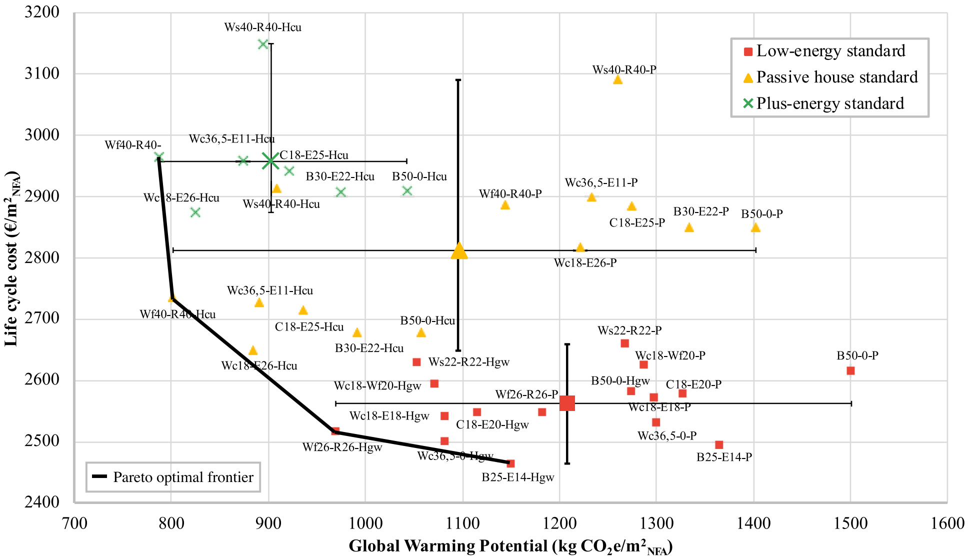

Fig. 9 Cost-environmental impact diagram for the 37 two-storey residential building scenarios over a reference study period of 50 years

assumed input parameters, a higher life cycle cost must be accepted to reduce the GWP impact.

Using the Pareto optimality logic, four pareto optimal solutions (PE-Wf40-R40-Hcu, P-Wf40-R40-Hcu, L-Wf26-R26-Hgw, L-B25-E14-Hgw) can be identified. For visualisation, the Pareto optimal frontier (solid line) based on the 37 defined scenarios was added as shown in Fig. 9.

4 Discussion

This study presents the life cycle environmental impact and cost of 37 scenarios with different energetic standards. These scenarios are based on common building practice and technical feasibility by varying the construction material, the insulation material and the technical building equipment. The analysed scenarios represent more than half of the possible cases that can be created. Moreover, according to the theory of probability and statistics, the minimum number of scenarios is 16 in order to obtain unbiased results. Therefore, these criteria, which were taken into account when creating the scenarios, allow for a robust and unbiased population of the cases studied. For the selected 37 scenarios of the presented case study, the improvement of the energetic standard in terms of embodied impacts has to be discussed from two perspectives. On the one hand, the improvement from 'low-energy' standard to 'passive house' standard results in a significant increase in the embodied impacts. This is due to the use of thicker construction and insulation materials. On the other hand, there is an insignificant decrease in embodied impacts when improving the energetic standards from 'passive house' standard to 'plus-energy' standard. However, this statement cannot be generalised and is due to the fact that, firstly, four of the seven 'plus-energy' standard scenarios are wooden buildings and, secondly, different technical building equipment were used due to the technical feasibility, i.e. no pellet boilers are used in the 'plus-energy' standard buildings.

Regarding the operational phase, an improvement in energetic standards leads to a reduction in operational impact. This is due to the reduction in the energy demand. It is important to mention that the energy demand for heating, cooling and ventilation has been taken into account and that the total energy demand of the 'plus-energy' standard is covered by PV electricity production.

In terms of the total environmental impact, the scenarios with the 'plus-energy' standard show on average the lowest GWP values, equal to 908.5 kg CO_2e/m^2_{NFA} which are completely allocated to the building materials and components. The GWP impacts obtained for scenarios with the 'plus-energy' standard are 70% lower than the impacts of traditional Austrian buildings published in previous studies (e.g. Passer et al. 2012). Furthermore, the environmental impacts of the 'plus-energy' standard buildings are almost equal to the environmental impacts of an innovative Austrian timber building created as part of a pilot project entitled '+ERS-Plus Energy Network Reininghaus Süd' (Hoxha et al. 2020a). When compared with buildings located in different countries, the impacts of the two-storey building assessed in this work can be assigned to the group of new advanced buildings (Röck et al. 2020). The comparison supports the development of scenarios that use the 'plus-energy' standard and underlines the robustness of the GWP results. However, it is not possible to achieve the 2050 targets by merely improving the energetic standard of buildings with a reduction in the operational environmental impacts of new projects (Hoxha et al. 2020b). Further reductions, and especially in the embodied impacts, will be necessary.

To perform the LCCA, all 37 scenarios were calculated based on a bottom-up approach. The obtained results indicate that, on average, the three considered energetic standards generate a life cycle cost between 2562 €/m^2_{NFA} and 2958 €/m^2_{NFA}. This range of calculated life cycle costs for the two-storey building is verified by the fact that they fall within the range provided in the construction cost index for new buildings (Baukosteninformationszentrum 2018). The construction cost index is an important metric in the field of construction cost planning that shows the evolution of construction prices over time. In this context, the underlying construction cost databases comprise several thousand billed projects on new buildings, old buildings and outdoor facilities. Furthermore, the additional construction cost calculated in this study (i.e. 12.1%) when comparing scenarios built to the 'low-energy' standard and 'passive house' standard are also in line with other studies (Schöberl et al. 2011). Studies on cost benchmarks for 'plus-energy'-standard buildings are still rare, as the construction of 'plus-energy' houses is not yet state-of-the-art.

4.1 Critical remarks

The research design and the methodological approach used in this study can also be applied to other countries. However, the energetic standards have both different names and classifications based on the national or regional energy performance regulations. EU member states are obliged to transpose the Energy Performance of Buildings Directive (EPBD) from the European Parliament into national law. According to the EPBD, all new buildings must be constructed as nearly zero-energy houses from 2021 onwards. This requirement has already been applied to new buildings that have been built for state authorities since 2019 (European Commission 2010).

These results, therefore, apply primarily to the Austrian context and must be adapted to fit specific circumstances in other countries.

In the present study, we calculated the environmental impact of buildings using a 0/0 approach. As the aim of the study was not to address biogenic carbon from bio-based materials, the 0/0 approach can be considered the most understandable and robust method (Hoxha and Passer 2021), although the 0/0 approach allows us to identify discrepancies in the range of 30% compared to the dynamic impact calculation method, which is considered more reliable, especially for bio-based materials (Hoxha et al. 2020a). However, the conclusions we have reached are not influenced by the uncertainties associated with the evaluation method.

Due to the application of fixed calculation parameters for the dynamic LCCA, the additional cost for the construction of buildings with a higher energetic standard (e.g. 'passive house' or 'plus-energy' buildings) cannot be amortised by the savings based on the underlying assumptions in the LCCA, regarding the operational cost over the life cycle of 50 years. This result is also consistent with Galimshina's study on the analysis of climate-friendly and cost-effective renovation scenarios, which found that the investment for renovation measures in buildings with good energy performance is not paid off by the operational savings (Galimshina et al. 2021). One sensitive parameter regarding the calculation of the operational cost is for example the escalation rate (energy), whereby an increase in the annual escalation rate (energy) can result in an amortisation of the additional construction cost within the different energetic standards within 50 years. Therefore, we performed a sensitivity analysis for the escalation rate (energy) by using three additional escalation rates (energy). Considering the average LCC of the energetic standards, an increase in the escalation rate (energy) to 6% does not result in an amortisation of the increased construction cost. At an escalation rate (energy) of 8%, the average LCC of the 'plus-energy' standard scenarios is already lower than that of the 'passive house' standard scenarios. At an escalation rate (energy) of 10%, the 'plus-energy' standard scenarios represent the lowest LCC, whereby the increased construction costs are paid off over the 50-year reference study period due to the low or non-existent operational cost. The results have been added to the supplementary materials.

4.2 Limitations

The results of this study must be interpreted based on the 37 chosen scenarios. Therefore, when comparing two scenarios or two energetic standards, the used construction materials, insulation materials and technical building equipment must be taken into account. In this context, due to the technical feasibility the 'plus-energy' standard does not include pellet boilers, as in practice these are implemented with heat pumps.

In conducting the sustainability assessment, only the installed materials and the technical building equipment were considered. No use of alternative materials such as hemp or straw was investigated. In addition, no possible optimisation of materials was considered, such as CO_2-optimised concrete or CO_2-optimised steel production.

Limitations regarding the applied methods arise in the LCA in the choice of environmental indicators. Due to the large amount of data, in this study we only addressed the environmental indicator GWP. Regarding the comparison of embodied impacts between 'passive house' standard and 'plus-energy' standard, it must be mentioned that the comparison based on average values is not significant (see Table 2). This insignificance results from the small number of scenarios within the plus-energy' standard (i.e. 7 scenarios). However, if we compare the same building types between 'passive house' standard and 'plus-energy' standard (i.e. same construction material, same insulation material, same technical building equipment), the embodied impacts are higher due to the additional PV in the 'plus-energy' standard buildings (pls. see supplementary materials).

Another limitation also occurs within the LCCA. In the present study, the LCCA based on the EN 16627 (CEN/TC 350 2015) was applied. The whole life cycle cost (WLC) approach, which includes additional costs such as externalities, non-construction cost or income, was not taken into account.

In the course of dynamic LCCA, values based on literature were assumed for calculation parameters such as discount rate, inflation rate, escalation rate (energy) and escalation rate (construction services). Since these parameters have an increasing influence on the LCC results with increasing reference study period, varying ranges for the parameters as well as sensitivity and risk analyses have to be performed to validate the LCCA results.

5 Conclusions

To ensure a cost-optimal environmental improvement of buildings, it is crucial to conduct an eco-efficiency assessment during the design process of energy-efficient buildings. We referenced the well-established energetic standards used in Austria and the main construction types (i.e. brick, concrete, wood-concrete and wood-frame or wood-solid construction) and combined these to create new building scenarios. Additional combinations of different technical building equipment (pellet heating and different types of heat pumps) were considered. In this study, we conducted an LCA and an LCCA of 37 scenarios with three defined energetic standards (i.e. the 'low-energy', 'passive house' and 'plus-energy' standards) for a two-storey residential building situated in Austria.

This study shows how improving the energetic standard of buildings can reduce environmental impacts with slightly increased life cycle costs. The results enable us to conclude that improving the energetic standard reduces the environmental impacts. Overall, it was possible to reduce the GWP impacts by 300 kg CO_2e/m^2_{NFA} or 24.8% when the energetic standard was improved from the 'low-energy' to the 'plus-energy' standard. The largest range of reduction of impacts between one energetic standard and the next better one (i.e. 207 kg CO_2e/m^2_{NFA}) was observed when the standard was improved from a 'passive house' to a 'plus-energy' standard. On the other hand, improving the energetic standard increased the cost by 547 €/m^2_{NFA} or 22.7%. The largest increment between one energetic standard and the next better one, equal to 256 €/m^2_{NFA}, was allocated to the improvement of the energetic standard from the 'passive house' to the 'plus-energy' standard. A deeper analysis of the results for these 37 scenarios shows that the value of the GWP indicator was reduced by minimising the impacts of the operational stage, while the LCC of the building increased due to construction costs in materials and technical building equipment.

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Data availability All data generated or analysed during this study are included in this published article and its supplementary information files.

Declarations

Competing interests The authors declare no competing interests.

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BUILDING COMPONENTS AND BUILDINGS

Transition of the procurement process to Paris-compatible buildings: consideration of environmental life cycle costing in tendering and awarding

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Abstract

Purpose The greenhouse gas (GHG) emissions caused by the construction industry account for an enormous share of total global CO_2 emissions. The numerous construction activities therefore continue to reduce the remaining carbon budget. One lever for the reduction of these GHG emissions lies in the procurement process of buildings. For this reason, a process model was developed that takes embodied and operational emissions into account in the tendering and awarding phase of buildings.

Methods To validate the developed theoretical framework, environmental life cycle costing (eLCC) was conducted on a single-family house case study, taking into account external cost caused by GHG emissions. Various shadow prices were defined for the calculation of external cost to identify changes in award decisions. We further investigated a results-based climate finance (RBCF) instrument, i.e., the GHG emission bonus/malus, to demonstrate an approach for calculating Paris-compatible cost (PCC) scenarios.

Results We show that an award decision based on life cycle costing (LCC) leads to a 12% reduction in GHG emissions. A further reduction in GHG emissions can be achieved by awarding contracts based on eLCC. However, the required shadow prices within the eLCC awards to influence the award decision are quite high. With the development of the LCA-based bonus/malus system, PCC scenarios can be determined at sufficient shadow prices, and further GHG emission reductions can be achieved.

Conclusions Since the implementation of LCA and LCC in the tendering and awarding process is currently not mandatory, in this context, the next step towards Paris-compatible buildings must first be taken by the awarding authorities as well as the policy-makers. However, the application of the LCA-based bonus/malus system and thus the awarding of contracts according to PCC scenarios show the enormous GHG emissions reduction potential and thus represent an innovative and sustainable framework for an adapted procurement process.

Keywords Environmental life cycle costing · External cost · Life cycle assessment · Carbon price · Shadow price · Results-based climate finance · Building procurement · Emission reduction · Sustainable construction

Communicated by Vanessa Bach.

Highlights

- Award decision based on conventional life cycle costing results in reduction of GHG emissions.
- Further reduction in GHG emissions can be achieved by awarding according to environmental life cycle costing.
- Paris-compatible cost scenarios can be determined with the LCA-based bonus/malus system.
- By Paris-compatible cost scenario awarding, GHG emission reductions can be achieved at a shadow price of 26€/tCO_2eq.
- Further reduction in GHG emissions can be achieved by awarding according to Paris-compatible cost scenario considering higher shadow prices.

Extended author information available on the last page of the article

1 Introduction

As part of the Paris Agreement, also known as COP21, 197 nations committed to keep global warming to 1.5–2 °C over pre-industrial levels (United Nations Framework Convention on Climate Change (UNFCCC) 2016). To do this, major efforts must be undertaken to pinpoint emission reduction plans in each industry with a high carbon footprint. Building-related activities account for 37% of the world's greenhouse gas (GHG) emissions (United Nations Environment Programme (UNEP) 2021) and should therefore be a central focus point. In Austria, a recent estimate shows that the "field of action" buildings is responsible for yearly GHG emissions of 22 to 31 Mt CO_2eq, depending on the assessment

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method, i.e., bottom-up process-based Life Cycle Assessment (LCA) or top-down input–output LCA. In particular, residential buildings are responsible for at least 65% of these emissions (Truger et al. 2022). According to the Paris Agreement, Austria's maximum emission budget by 2050 ranges between 1000 and 1500 million tonnes of CO_2eq. (Meyer and Steininger 2017). If emissions are not decreased below their current level, the emission budget will run out between 2028 and 2035 (Schleicher and Steininger 2017). However, due to the intersectoral nature of building-related activities, as represented by their "field of action," translating a national carbon budget into specific targets for buildings is no trivial task. Numerous European nations have already determined carbon budgets for their own building stocks, and a preliminary estimate was also calculated in Austria by combining top-down and bottom-up methods (Hoxha et al. 2020). Nevertheless, the notion of a carbon budget for buildings is not always unanimously agreed upon, and several methods of calculation can be deemed reasonable (Habert et al. 2020). There is, consequently, not yet a consistently defined Paris-compatible carbon budget for buildings in Austria.

No matter the target or the budget, in light of the high contribution of buildings' activities to climate change (Truger et al. 2022), it is clear that decreasing the environmental impacts associated with buildings is required, to ensure Austria's path to a Paris-compatible vision. In addition, due to their particularly long lifespan, the choices made for buildings constructed today largely determine the level of their long-term environmental impacts (Frischknecht et al. 2019). This is why the scientific literature has put remarkable efforts in identifying emission reduction strategies for buildings, whether targeting the operational emissions, i.e., emissions coming from the functioning of the building (Hoxha and Jusselme 2017; Lasvaux et al. 2017; Drouilles et al. 2019), or the embodied emissions, i.e., emissions related to the materials, transport, construction, and end-of-life (Alig et al. 2020; Zhong et al. 2021; Alaux et al. 2023). Trade-offs between embodied and operational emissions in order to improve the life cycle performance of buildings have also been highlighted in multiple studies (Mirabella et al. 2018; Lützkendorf and Balouktsi 2016). To be able to properly assess the estimated reductions in GHG emissions, these studies usually rely on scientific environmental assessments, such as LCA, a reliable methodology based on ISO 14040/14044 (International Organization for Standardization (ISO) 2006a, b), which was adapted into the specific European standards EN 15978 for buildings (CEN/TC 350 2011) and EN 15804 for building products (CEN/TC 350 2022). However, further emission reduction strategies are still being investigated, especially for the embodied emissions, as the current technological knowledge might not be enough to ensure the whole decarbonization of buildings (Alaux et al. 2022). Having a deep knowledge about GHG emissions reduction strategies is a prerequisite, but is not sufficient to guarantee their implementation in practice. The assessment of building performance taking into account the entire life cycle has been recommended by leading scientists of the Life Cycle Sustainability Assessment Community for decades and declared as a prerequisite for the implementation of sustainable construction (Birgisdottir et al. 2017; Hollberg et al. 2019; Lützkendorf 2021). In this context, further studies emphasize the importance of the systemic interrelationships of early design decisions and their impact on environmental, economic, and sociocultural and functional as well as technical quality of buildings (Kreiner et al. 2015; Scherz et al. 2018).

Currently, the vast majority of decisions still relies on construction cost-based evaluation, despite the availability of developed life cycle costing (LCC) methods, which can be divided into conventional LCC, environmental LCC (eLCC), and societal LCC, being applied for several years in research and (voluntary) certification schemes (e.g., ÖGNI/DGNB and ÖGNB) (Flöegl 2012; Kohler 2010; Langdon 2007; Wübbenhorst 1984). While conventional LCC only includes cost that occur directly within the life cycle of a product, eLCC includes at least the external cost caused by environmental impacts (Ciroth et al. 2008). A guide on application of different LCC methods related to LCA and SimaPro software have been published recently (Ingemarsdotter 2022).

Another recent study on the implementation of LCA and environmental footprint methods in the public procurement stated that the inclusion of LCA-based approaches in the public procurement practice is quite new. In this context, the study also investigated the inclusion of LCC and external cost based on 207 tenders and 17 court cases (Schreiber et al. 2021). eLCC which goes even further by internalizing environmental externalities (Ciroth et al. 2008) and whole life costing (WLC), which additionally includes next to conventional LCC also externalities, non-construction cost, and income (ISO 2008), is mostly not considered (Parikka-Alhola et al. 2012; Cheng et al. 2018; Schreiber et al. 2021). This is especially true concerning the procurement process of buildings. Moreover, the literature identified obstacles to its implementation. These obstacles were classified into five categories, (i) methodological obstacles, (ii) organizational obstacles, (iii) economic obstacles, (iv) legal obstacles, and (v) political obstacles, in a review article on LCA implementation in procurement of buildings (Scherz et al. 2022a). In the current schemes, initiatives to reduce GHG emissions (which might include additional construction cost) are not supported nor encouraged, and there is scarce literature on a possible inclusion of LCA and eLCC in the procurement process of buildings. In particular, the tendering and awarding phases of the process are critical; in the early design steps of a building, the available information concerning the building is incomplete, but the possibility to influence the environmental impacts is the highest (Kohler and Moffatt 2003). The sooner measures to decrease the environmental impacts of a building can be estimated (in the building design process),

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the more effective it will be, in terms of GHG emissions reduction as much as in terms of cost. The common EU framework level(s), which integrate LCC and LCA in its core-objectives form the early design steps of a building (Dodd et al. 2021), shows first steps of interest in that direction, and that there is much to gain in incorporating eLCC in the procurement process of buildings. Therefore, this article addresses three main research questions:

1. How can GHG emission reduction be influenced by using eLCC within the tendering and awarding of buildings?
2. How high must the shadow price be set to ensure that contracts are awarded to more environmentally friendly bids?
3. What are possible enhancement strategies for residential buildings to move towards a Paris-compatible vision?

To answer these questions, firstly, we used eLCC on a single-family house case study with 37 building scenarios based on LCA and LCC results published in Scherz et al. (2022b). For this first exploratory study, it was decided to focus solely on residential buildings, as they represent a large majority of the yearly GHG emissions from the Austrian building sector (Statistik Austria 2022; Truger et al. 2022). Secondly, we applied the theoretically developed process model, the so-called LCA-based bonus/malus system, for demonstrating an approach to calculate Paris-compatible cost (PCC) scenarios for 37 building scenarios. Thirdly, we analyzed the effects of the level of shadow prices and their influence on the award decision by calculating environmental break-even points.

The novelty of this study stems from the demonstration of an approach to calculate PCC scenarios as criterion for buildings award decisions based on the LCA-based bonus/malus system, which enables the award of contracts according to more environmentally friendly bids. Furthermore, the analyzed shadow prices in the case study under investigation confirm that the current carbon pricing instruments are set too low. This article aims to take a significant step forward in environmental procurement of buildings, in that awarding authorities no longer award contracts on the basis of construction cost, but instead take into account, in particular, the whole life cycle of buildings. This adapted approach to tendering and awarding also encourages bidders to increasingly implement innovative sustainable building projects in order to demonstrate their environmental advantage over traditional tendering and awarding procedures, as well as over other bidders.

2 Materials and methods

The results and findings of this study are based on a developed theoretical framework for considering GHG emissions in building procurement. The aim of this study is to apply the eLCC within the developed framework and to validate them by using a single-family house case study.

2.1 Tendering and awarding process of buildings

In Austria, the Federal Procurement Act can be used as the basis for contracts for the tendering and awarding of buildings. While private clients are not required to apply the Federal Procurement Act, public awarding authorities are required to comply with it. Section 5 of the Federal Procurement Act explains the principles of tendering. With regard to the performance specifications, § 103 stipulates the constructive or functional performance specification (§ 103 Federal Procurement Act 2018).

On the basis of the tender documents within the constructive performance specification, the bidders prepare their main bids by quoting unit prices for each service item. In this type of tender, changes or modifications by the bidders in the tender documents and in the bill of quantities are not permitted. However, the Federal Procurement Act also permits in § 96 the submission of other, better, more innovative or more favorable solutions by bidders in the form of alternative offers that make the existing know-how of the bidders available to the awarding authority (§ 96 Federal Procurement Act 2018). In the case of a tender with a functional performance specification, the awarding authority must define the performance target in accordance with the Federal Procurement Act (§ 103 (3) and § 104 (2)) as well as the suitability criteria, selection criteria (in the case of a two-stage award procedure), and award criteria (§ 103 and § 104 Federal Procurement Act 2018). Based on the defined performance target, the bidders are responsible for the design of the building and the preparation of the main offer, i.e., bill of quantities and unit prices. In this way, innovative ideas and the know-how of the bidders can be taken into account.

In the case study, the tender was based on the functional performance specifications. The prerequisite for such a tender is that the awarding authority formulates a detailed description of the building's performance target.

Furthermore, the award criteria must be defined by the awarding authority. In the course of the case study, it was assumed that only the lowest PCC scenario, i.e., lowest price after applying the LCA-based bonus/malus system, would be used for the award decision. To enable bidders to calculate the GHG emissions and the necessary eLCC, all calculation bases of the LCA, the LCC calculation as well as the shadow price and the carbon price for the results-based climate fund (RBCF) approach must be specified in the tender documents.

2.2 Case study

The case study is a two-storey single-family house, which was already observed in a previous research project Sölkner

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et al. (2014a, b) and further analyzed in Passer et al. (2016) and Scherz et al. (2022b). For this building, construction companies created 37 different scenarios and determined the bid prices. These 37 scenarios differ in their energetic standard (low-energy house, passive house, plus-energy house), their construction material (brick, concrete, wood-concrete, wood-frame, solid wood), their insulation material (expanded polystyrene (EPS), rock wool, no insulation), and their technical building equipment (pellet heating or heat pump). Figure 1 shows the floor plans and a section of the building as well as the explanation of the defined buildings codes. A detailed description of the case study as well as of the 37 scenarios can be found in the Supplementary Materials and in Scherz et al. (2022b).

2.3 Life cycle assessment–based bonus/malus system for calculating Paris-compatible cost scenarios

The LCA-based bonus/malus system is a theoretical framework for considering GHG emissions in building procurement decisions. The prerequisites for the application of the LCA-based bonus/malus system are (i) an adapted call for tender, (ii) the implementation of the LCA by the bidders as well as the verification of the LCA results by the awarding authority, (iii) the determination of a shadow price and a carbon price for the RBCF approach, and (iv) the establishment of a climate fund. Figure 2 shows the adapted tendering and awarding phase for the application of the LCA-based bonus/malus system.

For the calculation of the PCC scenarios, Eqs. (1) and (2) are used. The index n represents the number of bids.

$$PCC_n\ [€] = eLCC_n\ [€] + \text{GHG emissions}_{BONUS/MALUS\ n}\ [€] \quad (1)$$

where

$$\text{GHG emissions}_{BONUS/MALUS\ n}\ [€] = \left(GWP_n\left[tCO_2\ eq\right] - \frac{\sum_1^n GWP}{n}\right) \times RBCF_{carbon\ price}\ [€/tCO_2\ eq] \quad (2)$$

In the first step, the awarding authority must define all the information required for a tender in accordance with PCC scenarios in the tender documents. At the beginning, this includes the decision as to whether the tender is to be based on constructive or functional performance specifications. In

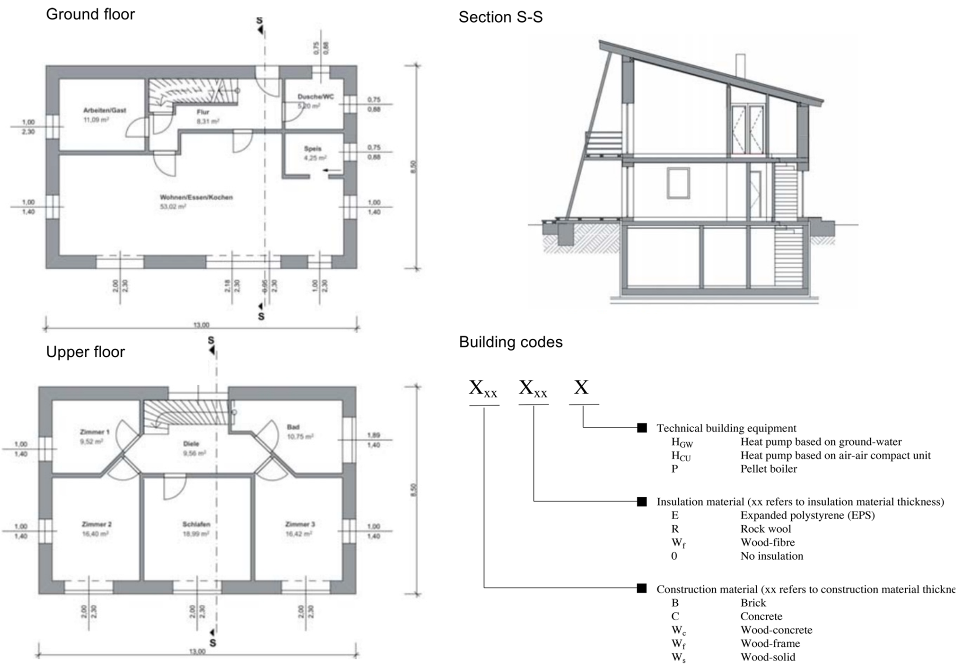

Fig. 1 Floor plans and cross section of the two-storey residential building and explanation of the defined building codes (Sölkner et al. 2014b; Passer et al. 2016; Scherz et al. 2022b)

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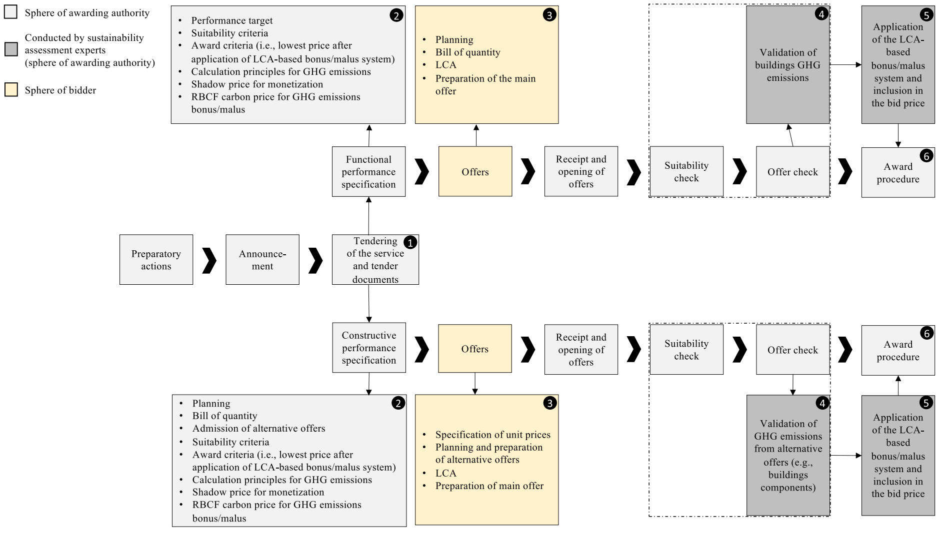

Fig. 2 Theoretical framework of the LCA-based bonus/malus system. Spheres of awarding authorities and bidders for the two tender types (i) tender with functional performance specifications and (ii) tender with constructive performance specifications

case of an award on the basis of a constructive performance specification, the awarding authority must define a precise performance target according to ÖNORM B 2110 (Austrian Standards Institute (ASI) 2013). In addition, suitability criteria, selection criteria (in the case of a two-stage award procedure) and award criteria must be defined. If this procedure is chosen, the awarding authority is responsible for the design of the building and the preparation of detailed bill of quantities, i.e., service items and quantity determination. Since the bidders are not allowed to change the constructive specifications, alternative offers must be permitted in this variant. If the functional performance specification is selected, alternative offers are not required, since in this variant, the bidders are responsible for the performance specifications and determination of quantities.

The second important step, for both performance specification types, is the definition of the principles for the calculation of the PCC scenarios. On the one hand, this means that all the necessary calculation parameters for performing the LCA, such as life cycle modules to be considered, reference study period, databases for background data, calculation software, data sets for energy mix, and service life data must be defined. On the other hand, all calculation parameters for the calculation of the eLCC must also be specified, such as inflation rate, interest rate, price increase rates, and energy prices. Finally, the shadow price and the carbon price for the RBCF approach must also be determined. If the know-how for conducting an LCA is not available within the organization of the bidders, they must seek the assistance of external sustainability assessment experts to conduct the LCA. This issue is particularly relevant for small and medium-sized enterprises, as they may not have the expertise to conduct a LCA themselves. This organizational obstacle can be overcome by using external experts, thus ensuring that the results of the LCA are reliable and credible. Assuming that all information are available and therefore the LCA and eLCC can be carried out, the bidders will prepare their planning including bill of quantities and submit the bids. In the considered case study, 37 valid offers, i.e., 37 different building scenarios, were submitted. After submitting, the offers must be checked for correctness. The awarding authority must also check the results of the LCA and eLCC. For this step, if there is a lack of expertise within the awarding authority, sustainability assessment experts can be consulted, similar to the bidders' sphere, to ensure a transparent and objective verification of the results. After reviewing the bids, the PCC scenarios of the 37 scenarios are calculated using the LCA-based bonus/malus system. For the calculation of the GHG emissions bonus/malus, the mean value of the GHG emissions of all submitted bids is

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determined (see Eq. (2)). The deviation of the GHG emissions from this mean value is then determined for each bid. If the bid is below the mean value, it is a more environmentally friendly bid, and a bonus is deducted from the bid price by monetization using the defined RBCF carbon price. If the offer is above the mean value, it is a non-environmental offer, and a malus is added to the bid price by monetization using the RBCF carbon price (see Eq. (1)).

2.4 Environmental life cycle costing

Life cycle costing (LCC) can be divided into the three types: (i) conventional LCC, (ii) environmental LCC (eLCC), and (iii) societal LCC (Ciroth et al. 2008). While conventional LCC only includes cost that occurs directly within the life cycle of a product, eLCC includes at least the external cost caused by environmental impacts. Societal LCC goes much further and includes all current and future external cost that can be monetized, such as impacts on, among others, public health, social well-being, job quality, and family life (Bickel and Friedrich 2005).

The term eLCC was first used in a study on the economic evaluation of municipal waste management systems (Reich 2005) in 2005 and derived from the term life cycle inventory-based LCC used by Rebitzer (2005).

The LCC framework for the application within the construction industry is standardized in the EN 16627, EN 15643–4, and ISO 15686–5 (CEN/TC 350 2012, 2015; ISO 2008).

Compared to the ISO 15686–5, which defines LCC for buildings and constructed assets (ISO 2008), the conventional LCC can be understood with the LCC in the narrower sense, which includes the cost groups construction cost, operation cost, maintenance cost, and end-of-life cost. While eLCC only includes external cost of environmental impacts, ISO 15686–5 also defines LCC in a broader sense under the term whole life costing (WLC), which takes into account not only externalities but also non-construction costs and income. Since in this study, only external cost due to GHG emissions calculated by the method of LCA are considered, the method eLCC as defined in Ciroth et al. (2008) is used and is calculated by using Eqs. (3) and (4). The index n represents the number of bids:

$$\text{eLCC}_\text{n}\ [€] = \text{LCC}_\text{n}\ [€] + \text{External cost}_\text{n}\ [€] \tag{3}$$

where

$$\text{External cost}_\text{n}\ [€] = GWP_n\ \left[\text{tCO}_2\ \text{eq}\right] \times \text{shadow price}\ [€/\text{tCO}_2\text{eq}] \tag{4}$$

The GWP for the 37 building scenarios were calculated by using the LCA method in Scherz et al. (2022b). The method of LCA has become established for evaluating the environmental impacts of buildings. The calculation principles of LCA are defined in standards ISO 14040 and ISO 14044 (ISO 2006a, b). In addition, standard EN 15978 regulates the application of LCA in the construction industry (CEN/TC 350 2011). Detailed description of the system boundaries, the assumed reference study period (50 years), and further assumptions for the LCC and LCA calculations can be found in Scherz et al. (2022b).

2.5 Carbon pricing

Social cost of carbon are used to describe the costs resulting from the impact of emitting an additional ton of CO_2eq on the environment and human health (Nordhaus 2017). These cost are not included in the market prices from products or services and are therefore not borne by the stakeholders directly involved, such as the manufacturers, suppliers, consumers, or users. Social cost of carbon can be determined by various carbon pricing instruments. The two main mandatory carbon pricing instruments are the emission trading system (ETS) and carbon taxes (The World Bank 2021). In Europe, the ETS follows the cap-and-trade principle. Under this system, participating entities are set an upper limit (cap) on their GHG emissions, and allowances are allocated for their emissions. If this limit is exceeded or not reached, certificates can be bought from or sold to other entities (European Commission 2021). Over time, this limit is reduced, resulting in a reduction in emissions. In relation to the construction industry, the major steel, cement, and brick manufacturers, among others, are subject to the European ETS (Environment Agency Austria 2022). Carbon taxes were already proposed in 1973 (Berdik 2014) and have been adopted in some countries since many years (The World Bank 2021). In Austria, a carbon tax of 30€/tCO_2eq was established in 2022 and taxes the import and combustion of fossil fuels. Entities that are already subject to the ETS are exempt from the carbon tax and will not be taxed twice. In Austria, the carbon tax is to be increased to 55€/tCO_2eq by 2025 (International Carbon Action Partnership 2022). In contrast to these mandatory carbon pricing instruments, there are also forms of voluntary carbon pricing instruments. These include RBCF and internal carbon pricing types such as internal carbon fees and shadow prices. In RBCF, target values such as CO_2eq benchmarks for emission reduction are set in advance and usually evaluated by third parties after project completion. Based on the achieved outputs and the defined emission reduction targets, fundings are paid out. The internal carbon fee is an internal monetary value within entities for one ton of CO_2eq. This fee generates revenues, which can then be invested in the entities' emission reduction targets. In contrast, the shadow price is a theoretical price that supports entities in the long-term transition to low-carbon technology. The shadow price is defined as the price that reflects social cost and benefits (Kanbur 1991).

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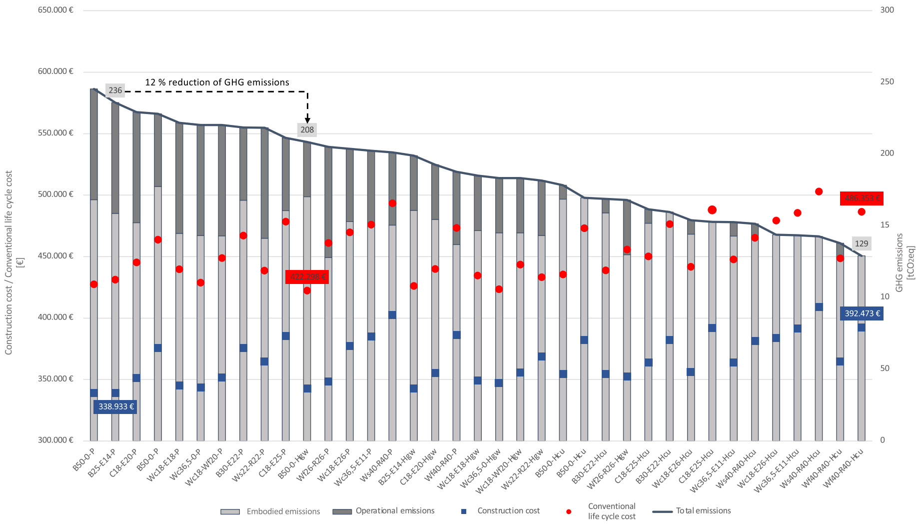

Fig. 3 Comparison of awarding according to construction cost and according to conventional LCC illustrating the GHG emission reduction potential

Studies show that companies mostly apply a higher shadow price than proposed by governments through ETS and carbon taxes (The World Bank 2021).

In order to calculate the external cost, values from the scientific literature were used to define the shadow prices. In the literature, there are already numerous studies on the definition of carbon prices (Rennert et al. 2022; Arendt et al. 2020; CCCA-Experten 2020; Schneider-Marin and Lang 2020; De Nocker and Debacker 2017; Allacker and De Nocker 2012). The defined shadow price range and the RBCF carbon price range set for this study, i.e., 50 €/tCO_2eq to 400 €/tCO_2eq is based on the CCCA experts' factsheet (CCCA-Experten 2020). This initial value of 50 €/tCO2eq is also in line with the European Union average value of carbon prices (The World Bank 2021).

3 Results

3.1 Award based on conventional LCC

The eLCC results of the 37 buildings scenarios build upon the LCA and LCC results published in Scherz et al. (2022b) and are analyzed from the perspective of the award decision. The results of the conventional LCC show that already by considering the application of conventional LCC in the tender documents, their calculation and finally the award according to the lowest conventional LCC bring a reduction of GHG emissions. Figure 3 shows, on the one hand, the total emissions (right axis), i.e., embodied emissions and operational emissions, of the 37 scenarios based on the LCA, ranked in descending order from the scenario with the highest emissions (50-cm brick construction, no insulation material and pellet heating system; B_{50}-0-P) to the scenario with the lowest emissions (40-cm wood-frame construction, 40-cm rock wool insulation, and heat pump system; Wf_{40}-R_{40}-Hcu) and, on the other hand, the construction cost based on the bills of quantities and the conventional LCC (left axis). Additionally highlighted in the figure are the construction cost (written in blue) and the conventional LCC (written in red) of each scenario. An award according to construction cost leads to the acceptance of scenario B_{25}-E_{14}-P (25-cm brick construction, 14-cm EPS insulation, and pellet heating system) with total emissions of 236 tCO_2eq[1] (which is almost the most GHG emitting scenario). In the case of an award based on conventional LCC, scenario B_{50}-0-H_{gw} (50-cm brick construction, no insulation material and heat pump system) with total emissions of 208 tCO_2eq[1] is awarded the contract. This means that, by awarding contracts according to conventional LCC, approximately 12% of GHG emissions can be saved.

[1] The detailed LCA and LCC results can be found in the supplementary materials of Scherz et al. (2022b).

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A comparison of awarding contracts according to construction cost and conventional LCC on the basis of the cost difference seems to show that awarding contracts according to conventional LCC results in a higher amount in cost of around 20%. In this context, however, this cost difference cannot be described as an additional cost, since the awarding according to construction cost (338.933 €)[1] does not take into account the operational cost over 50 years. Therefore, in this case, the conventional LCC of the scenario with 25-cm brick construction, 14-cm EPS insulation, and pellet heating system (B_{25}-E_{14}-P) over 50 years is higher than the lowest conventional LCC scenario with 50-cm brick construction, no insulation material, and heat pump system (B_{50}-0-H_{gw}), and the GHG emissions are reduced, which results in a win–win solution. For the maximum reduction in GHG emissions, the award has to go to the scenario with 40-cm wood-frame construction, 40-cm rock wool insulation, and heat pump system (Wf_{40}-R_{40}-H_{cu}). This allows a further 38% reduction in GHG emissions compared to the awarded scenario with 50-cm brick construction, no insulation material, and heat pump system (B_{50}-0-H_{gw}) according to conventional LCC. In this case, however, we are talking about additional cost, since the conventional LCC of the scenario with 40-cm wood-frame construction, 40-cm rock wool insulation and heat pump system (Wf_{40}-R_{40}-H_{cu}) is around 13% higher than the award to scenario with 50-cm brick construction, no insulation material, and heat pump system (B_{50}-0-H_{gw}).

3.2 Award based on environmental LCC

In addition, the GHG emissions savings potential when awarded according to eLCC was investigated based on the 37 scenarios. Figure 4 shows three different eLCCs based on three different shadow prices, i.e., 50 €/tCO_2eq, 200 €/tCO_2eq, and 400 €/tCO_2eq. The results show that at a shadow price of 50 €/tCO_2eq (in yellow on the graph), the cheapest scenario according to eLCC is the scenario with 50-cm brick construction, no insulation material, and heat pump system (B_{50}-0-H_{gw}). Compared to the award according to conventional LCC (see Fig. 3), the award according to eLCC at this defined shadow price does not bring any change in the award decision, and thus no further GHG emissions savings potential. However, if a shadow price of 200 €/tCO_2eq (in green) or 400 €/tCO_2eq (in blue) is set and awarding according to eLCC is used, the scenario with 36.5 cm wood-concrete construction, no insulation material, and heat pump system ($Wc_{36,5}$–0-H_{gw}) is awarded the contract. This means that a further reduction in GHG emissions of around 12% is possible.

Comparing the cost of awarding according to eLCC at a shadow price of 200 €/tCO_2eq and 400 €/tCO_2eq with awarding according to conventional LCC results in additional

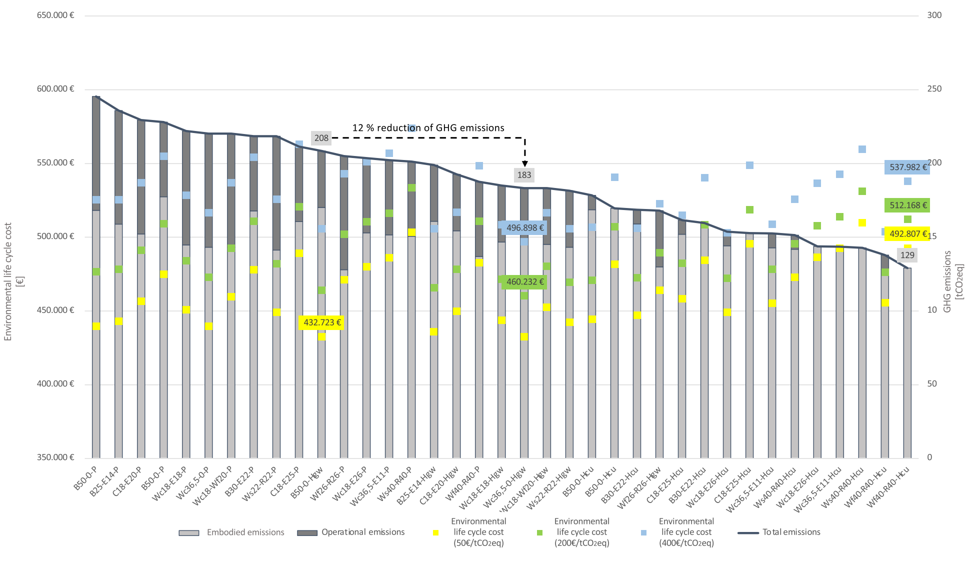

Fig. 4 Comparison of awarding according to eLCC by applying, three different shadow prices (50 €/tCO_2eq, 200 €/tCO_2eq, 400 €/tCO_2eq) and illustrating the GHG emissions reduction potential

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cost of 8% and 15%, respectively. Comparing the cost within the eLCC award, there is about 6% additional cost between eLCC at a shadow price of 50 €/tCO_2eq to eLCC at a shadow price of 200 €/tCO_2eq. In order to execute the scenario with 40-cm wood-frame construction, 40-cm rock wool insulation, and heat pump system (Wf_{40}-R_{40}-H_{cu}) with the lowest total emissions, and therefore achieve a GHG emissions reduction of around 38%, an additional cost of 12% is incurred at a shadow price of 50 €/tCO_2eq and when awarded according to eLCC. The additional cost between the award to the lowest eLCC scenario at a shadow price of 200 €/tCO_2eq. and the award to the most environmental scenario with 40-cm wood-frame construction, 40-cm rock wool insulation, and heat pump system (Wf_{40}-R_{40}-H_{cu}) amount to 10% at an achieved GHG emission reduction of 30%. The additional cost between the award to the lowest eLCC scenario at a shadow price of 400 €/tCO_2eq. and the award to the most environmental scenario with 40-cm wood-frame construction, 40-cm rock wool insulation, and heat pump system (Wf_{40}-R_{40}-H_{cu}) amount to 13% also at an achieved GHG emission reduction of 30%.

3.3 Award based on Paris-compatible cost scenarios

In order to reduce the shadow price and still achieve a further GHG emissions reduction, the awarding according to PCC scenarios was introduced. This means that the LCA-based bonus/malus system is additionally applied to the calculated environmental LCC. Figure 5 shows the PCC scenarios at three different shadow prices and carbon prices for the RBCF approach, i.e., 50 €/tCO_2eq. (in yellow), 200 €/tCO_2eq. (in green), and 400 €/tCO_2eq. (in blue).

The results show that awarding by PCC scenarios at a shadow price and RBCF carbon price of 50 €/tCO_2eq results in a different award decision (scenario with 36.5-cm wood-concrete construction, no insulation material, and heat pump system; $Wc_{36,5}$–0-H_{gw}) than awarding by eLCC at a shadow price of 50 €/tCO_2eq. (scenario with 50-cm brick construction, no insulation material, and heat pump system; B_{50}-0-H_{gw}).

Thus, already at this set shadow price and by applying the RBCF approach, i.e., GHG emissions bonus, the further 12% GHG emission savings are achievable. While no further GHG emissions reduction can be achieved with an awarding according to PCC scenarios at 200 €/tCO_2eq, a further GHG emissions reduction of around 25% can be reached with a shadow price and RBCF carbon price of 400 €/tCO_2eq. In this case, the scenario with 40-cm wood-frame construction, 40-cm rock wool insulation, and heat pump system (Wf_{40}-R_{40}-H_{cu}) is awarded the contract.

Comparing the cost of awarding according to PCC scenarios at a shadow price and RBCF carbon price of 50 €/tCO_2eq with awarding according to conventional LCC results in additional

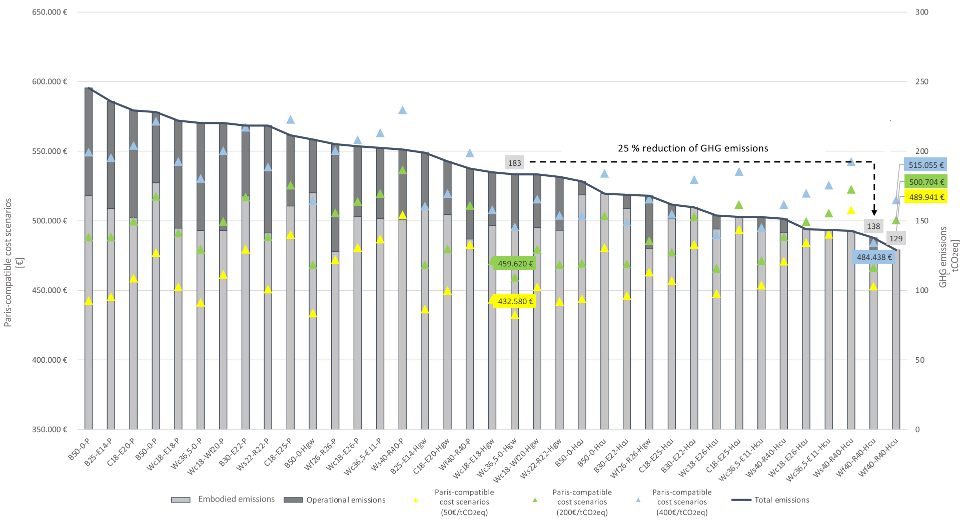

Fig. 5 Comparison of awarding according to Paris-compatible cost scenarios by applying, three different shadow prices and RBCF carbon prices (50€/tCO_2eq, 200€/tCO_2eq, 400€/tCO_2eq) and illustrating the GHG emissions reduction potential

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cost of around 2%. Thus, awarding by PCC scenarios at a shadow price and RBCF carbon price of 50 €/tCO_2eq (the scenario with 36.5-cm wood-concrete construction, no insulation material, and heat pump system; $Wc_{36,5}$–0-H_{gw}) compared to awarding by eLCC at a shadow price of 200 €/tCO_2eq (the scenario with 36.5-cm wood-concrete construction, no insulation material, and heat pump system; $Wc_{36,5}$–0-H_{gw}) is about 6% less costly for awarding authorities.

Comparing the cost within the PCC scenarios award, there is about 11% additional cost between PCC scenarios at a shadow price and RBCF carbon price of 50 €/tCO_2eq to PCC scenarios at a shadow price and RBCF carbon price of 400 €/tCO_2eq for achieving a GHG emissions reduction of 25%. Between PCC scenarios award at a shadow price and RBCF carbon price of 200 €/tCO_2eq. and PCC scenarios at a shadow price and RBCF carbon price of 400 €/tCO_2eq, there are additional cost of 5% for the GHG emissions reduction of 25%. In order to execute the scenario with 40-cm wood-frame construction, 40-cm rock wool insulation, and heat pump system (Wf_{40}-R_{40}-H_{cu}) with the lowest total emissions and thus achieve a further GHG emissions reduction of around 7%, an additional cost of 6% is incurred at a shadow price and RBCF carbon price of 400 €/tCO_2eq. When awarded according to PCC scenarios at a shadow price and RBCF carbon price of 50 €/tCO_2eq, an additional cost of 12% is incurred for a GHG emission saving potential of 3%. When awarded according to PCC scenarios at a shadow price and RBCF carbon price of 200 €/tCO_2eq, an additional cost of 7% is incurred also for a GHG emission saving potential of 30%.

The detailed cost calculations for conventional LCC, eLCC, and PCC scenarios can be found in the Supplementary Materials.

3.4 Environmental break-even point and enhancement strategies for residential buildings

The results presented so far were based on the three defined shadow prices and RBCF carbon prices, i.e., 50 €/tCO_2eq, 200 €/tCO_2eq, and 400 €/tCO_2eq. In order to examine the impact of the shadow prices and the RBCF carbon prices in detail, environmental break-even points were identified for the 37 scenarios. The environmental break-even point is the level of the shadow price and RBCF carbon price at which the award decision, i.e., the scenario, changes, and therefore a further GHG emissions reduction, is achieved. For the determination of the environmental break-even point, the shadow price and RBCF carbon price was chosen from 0 €/tCO_2eq to 400 €/tCO_2eq in 1€ increments and applied to both the awarding according to eLCC and the awarding according to PCC scenarios.

Table 1 shows the awarded scenarios by (i) construction cost, (ii) conventional LCC, (iii) eLCC, and (iv) PCC scenarios. For the eLCC and PCC scenarios, the environmental break-even points are highlighted.

For the PCC scenarios awarding, this means that the first environmental break-even point is at a shadow price and RBCF carbon price of 26 €/tCO_2eq. At this price, the award decision changes from the scenario with 50-cm brick construction, no insulation material, and heat pump system

Table 1 Awarded scenarios by (i) construction cost, (ii) conventional life cycle cost, (iii) environmental life cycle cost, and (iv) Paris-compatible cost scenarios. For the environmental life cycle cost and the Paris-compatible cost scenarios, the environmental break-even points are highlighted and their GHG emissions reduction potentials are described[1]

Awarding based on	Cost [€]	Carbon price [€/tCO_2eq]	Scenario	Compared to scenario	Total GHG emissions	GHG emissions reduction potential	Enhancement strategies
Construction cost	338.933		B25-E14-P		236		
LCC	422.298		B50-0-H	B25-E14-P	208	12%	50-cm brick, no EPS insulation, heat pump
eLCC	432.580	50	B50-0-H		208		
eLCC	432.760	51	Wc36,5–0-H	B50-0-H	183	12%	36.5-cm wood-concrete
eLCC	524.947	553	Wc36,5–0-H		183		
eLCC	525.085	554	Wf40-R40-H	Wc36,5–0-H	129	30%	40-cm wood-frame, 40-cm rock wool insulation
PCC	428.063	25	B50-0-H		208		
PCC	428.253	26	Wc36,5–0-H	B50-0-H	183	12%	36.5-cm wood-concrete
PCC	473.320	276	Wc36,5–0-H		183		
PCC	473.455	277	Wf40-R40-H	Wc36,5–0-H	129	30%	40-cm wood-frame, 40-cm rock wool insulation

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(B_{50}-0-H_{gw}) to the scenario with 36.5 cm wood-concrete construction, no insulation material, and heat pump system ($Wc_{36,5}$–0-H_{gw}). The second environmental break-even point is at a shadow price and RBCF carbon price of 277 €/tCO_2eq. At this price, the award decision changes from the scenario with 36.5-cm wood-concrete construction, no insulation material, and heat pump system ($Wc_{36,5}$–0-H_{gw}) to the scenario with 18-cm wood-concrete construction, 26-cm EPS insulation material, and heat pump system (Wc_{18}-E_{26}-H_{cu}).

For the eLCC awarding, the environmental break-even points are higher. This means that the first environmental break-even point is at a shadow price of 51 €/tCO_2eq. At this shadow price, the award decision changes from the scenario with 50-cm brick construction, no insulation material, and heat pump system (B_{50}-0-H_{gw}) to the scenario with 36.5-cm wood-concrete construction, no insulation material, and heat pump system ($Wc_{36,5}$–0-H_{gw}). The second environmental break-even point is at a shadow price of 554 €/tCO_2eq. At this shadow price, the award decision changes from the scenario with 36.5-cm wood-concrete construction, no insulation material, and heat pump system ($Wc_{36,5}$–0-H_{gw}) to the scenario with 40-cm wood-frame construction, 40-cm rock wool insulation, and heat pump system (Wf_{40}-R_{40}-H_{cu}).

Based on the results of the calculations, five different types of reduction potentials for residential buildings can be derived within the case study under investigation. Within the first reduction potential in the tender documents, the awarding according to conventional LCC must be mandatory. In this case, it is not necessary to define a shadow price or RBCF carbon price because no external cost are considered within the conventional LCC. With this approach, savings in GHG emissions of approximately 12% can be achieved. Looking at the awarded scenario from a technical point of view, it is evident that in terms of the construction material, there is a change from a 25-cm brick construction with 14-cm EPS insulation material to a 50-cm brick construction without additional insulation material. Regarding the technical building equipment, a change from pellet heating to a heat pump system takes place.

Within the second reduction potential in the tender documents, the awarding according to PCC scenarios must be mandatory. In order to reach the first environmental break-even point, a shadow price and RBCF carbon price of 26 €/tCO_2eq must also be specified. With this approach, savings in GHG emissions of approximately 12% can be achieved. Looking at the awarded scenario from a technical point of view, it is evident that in terms of the construction material, a change from brick to wood-concrete takes place. Regarding the insulation material also in this scenario, no insulation material is necessary. Within the third reduction potential, also the awarding according to PCC scenarios must be allowed. Within this case and in order to reach the second environmental break-even point, a shadow price and RBCF carbon price of 277 €/tCO_2eq must be specified. With this approach, savings in GHG emissions of approximately 25% can be achieved. Looking at the awarded scenario from a technical point of view, the implementation of 40-cm wood-frame construction instead of 36.5-cm wood-concrete construction, the implementation of 40-cm additional rock wool insulation, and also the implementation of heat pump is required.

Within the fourth reduction potential in the tender documents, the awarding according to eLCC must be mandatory. In order to reach the first environmental break-even point, a shadow price of 51 €/tCO_2eq must also be specified. With this approach, savings in GHG emissions of approximately 12% can be achieved. Looking at the awarded scenario from a technical point of view, it is evident that in terms of the construction material, a change from 50-cm brick to 36.5-cm wood-concrete takes place. Regarding the insulation material in this scenario, also no insulation material is necessary. Within the fifth reduction potential, also the awarding according to eLCC must be allowed. Within this case and in order to reach the second environmental break-even point, a shadow price of 554 €/tCO_2eq must be specified. With this approach, savings in GHG emissions of approximately 25% can be achieved. Looking at the awarded scenario from a technical point of view, the implementation of 40-cm wood-frame construction instead of 36.5-cm wood-concrete construction, the implementation of 40-cm additional rock wool insulation, and also the implementation of heat pump is required.

3.5 Tendering and awarding according to Paris-compatible cost scenarios

Table 2 shows the results for each cost type, i.e., conventional LCC, eLCC, and PCC scenarios and its impact on the award decision at a defined shadow price and RBCF carbon price of 277 €/tCO_2eq.

Awarding according to PCC scenarios have implications for the awarding authority not only in terms of the scenario executed, but also in terms of the bid price. However, the additional cost incurred does not have to be covered entirely by the awarding authority, but is subsidized by the GHG emissions bonus if the award is made to a more environmentally friendly scenario. Setting a shadow price and RBCF carbon price of 277 €/tCO_2eq, awarding according to PCC scenarios, would result in a bid price of 486.903 € for the scenario with 40-cm wood-frame construction, 40-cm rock wool insulation, and heat pump system (Wf_{40}-R_{40}-H_{cu}). The bid price is always the price according to environmental LCC, as the PCC scenarios only represent fictitious bid prices for the Paris-compatible vision award.

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Table 2 Award decision in case of PCC scenarios awarding based on the LCA-based bonus/malus system at a fixed shadow price and RBCF carbon price of 277 €/tCO_2eq

	Life cycle assessment[b] [tCO2eq]	**Conventional life cycle cost[1] [€]**	**Environmental life cycle cost [€]**	**GHG emissions bonus/malus [€]**	**Paris-compatible cost scenarios [€]**
B50-0-P	245	431.312 €	496.657 €	13.715 €	510.372 €
B25-E14-P	236	427.549 €	495.537 €	16.358 €	511.896 €
C18-E20-P	229	445.297 €	508.824 €	11.897 €	520.721 €
B50-0-P	228	463.686 €	526.878 €	11.561 €	538.439 €
Wc18-E18-P	222	439.759 €	501.229 €	9.839 €	511.068 €
Wc36,5–0-P	220	428.817 €	489.836 €	9.389 €	499.225 €
Wc18-Wf20-P	220	448.814 €	509.830 €	9.386 €	519.215 €
B30-E22-P	218	467.021 €	527.543 €	8.892 €	536.435 €
Ws22-R22-P	218	438.550 €	499.060 €	8.880 €	507.940 €
C18-E25-P	211	478.419 €	536.974 €	6.925 €	543.898 €
B50-0-Hgw	208	422.298 €	480.050 €	6.121 €	486.171 €
Wf26-R26-P	205	461.045 €	517.841 €	5.165 €	523.006 €
Wc18-E26-P	204	469.867 €	526.270 €	4.772 €	531.042 €
Wc36,5-E11-P	202	476.025 €	532.073 €	4.417 €	536.490 €
Ws40-R40-P	201	493.416 €	549.167 €	4.121 €	553.288 €
B25-E14-Hgw	199	426.061 €	481.169 €	3.478 €	484.647 €
C18-E20-Hgw	193	440.046 €	493.411 €	1.735 €	495.146 €
Wf40-R40-P	188	473.439 €	525.410 €	341 €	525.751 €
Wc18-E18-Hgw	185	434.509 €	485.741 €	-398 €	485.344 €
Wc36,5–0-Hgw	183	423.567 €	474.349 €	-848 €	473.500 €
Wc18-Wf20-Hgw	183	443.563 €	494.342 €	-851 €	493.491 €
Ws22-R22-Hgw	181	433.336 €	483.609 €	-1.357 €	482.252 €
B50-0-Hcu	178	435.509 €	484.912 €	-2.228 €	482.684 €
B50-0-Hcu[a]	170	473.141 €	520.114 €	-4.657 €	515.457 €
B30-E22-Hcu	169	438.842 €	485.576 €	-4.897 €	480.679 €
Wf26-R26-Hgw	168	455.758 €	502.317 €	-5.072 €	497.245 €
C18-E25-Hcu	162	450.241 €	495.007 €	-6.864 €	488.143 €
B30-E22-Hcu[a]	160	476.476 €	520.705 €	-7.401 €	513.305 €
Wc18-E26-Hcu	154	441.690 €	484.304 €	-9.016 €	475.288 €
C18-E25-Hcu[a]	153	487.874 €	530.210 €	-9.293 €	520.917 €
Wc36,5-E11-Hcu	153	447.847 €	490.106 €	-9.372 €	480.734 €
Ws40-R40-Hcu	151	465.238 €	507.201 €	-9.667 €	497.533 €
Wc18-E26-Hcu[a]	144	479.322 €	519.178 €	-11.774 €	507.404 €
Wc36,5-E11-Hcu[a]	144	485.480 €	525.235 €	-11.875 €	513.360 €
Ws40-R40-Hcu[a]	143	502.871 €	542.404 €	-12.097 €	530.307 €
Wf40-R40-Hcu	138	448.721 €	486.903 €	-13.448 €	473.455 €
Wf40-R40-Hcu[a]	129	486.353 €	522.106 €	-15.877 €	506.229 €
	Mean value	Minimum value	Minimum value		Minimum value
	186	422.298 €	474.349 €		473.455 €
Award decision		B_{50}-0-H_{gw}	$Wc_{36,5}$–0-H_{gw}		Wf_{40}-R_{40}-H_{cu}

[a]Scenario is designed in the energetic standard "plus-energy house standard" [b]The detailed LCA and LCC results can be found in the supplementary materials of Scherz et al. (2022b)

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As a result, not the bidder with the scenario with 50-cm brick construction, no insulation material, and heat pump system (B_{50}-0-H_{gw}) with the lowest conventional LCC would get the award, but the bidder with the scenario with 40-cm wood-frame construction, 40-cm rock wool insulation and heat pump system (Wf_{40}-R_{40}-H_{cu}). This would subsequently lead to additional cost for the awarding authority of 13% and a GHG emissions reduction of 34% (208 tCO_2eq to 138 tCO_2eq). However, this bid price is reduced due to the application of the LCA-based bonus/malus system. Because the fictitious bid price according to the PCC scenario is 473.455 €, a GHG emissions bonus in the amount of 13.448 € is paid to the awarding authority by a climate fund (RBCF approach), reducing the additional cost to 11%. If the scenario with 50-cm brick construction, no insulation material, and heat pump system (B_{50}-0-H_{gw}) was to be awarded the contract, the bid price to be paid would be 480.050 € at a shadow price and RBCF carbon price of 277 €/tCO_2eq. In addition, the awarding authority would have to pay a GHG emissions malus in the amount of 6.121 € to the climate fund.

4 Discussion

Although the EU directive (European Parliament 2014) and the Federal Procurement Act in Austria (Federal Procurement Act 2018) allow the awarding based on the most economically advantageous tender (MEAT) and also explicitly mention the implementation of LCC and external cost based on LCA. However, in practice, building procurement is still based on price (Cheng et al. 2018). The results of this study show that with an adapted tendering and awarding procedure, GHG emissions can be reduced. By awarding contracts on the basis of conventional LCC instead of construction cost, up to 12% of GHG emissions can be reduced in the first step within the analyzed case study. This GHG emissions saving is achieved within the 37 scenarios with the application of heat pump systems instead of pellet heating systems. This is a reasonable strategy and therefore seems to be advisable for future residential buildings as well (Borge-Diez et al. 2022; Nematchoua et al. 2022). Nevertheless, it has to be mentioned that this result however strongly depends on the carbon content of the local electricity mix. However, the literature shows that the mandatory requirements of conventional LCC calculation in the tender as well as the awarding according to the lowest conventional LCC in the award phase are not applied in the current procurement practice. In this context, only a few studies analyze the implementation of conventional LCC in the building procurement process (Khalil et al. 2021; Lim et al. 2018; Dragos and Neamtu 2013).

Further GHG emissions reduction potential can be achieved by awarding contracts according to eLCC. Depending on the level of the shadow price (i.e., 50 €/tCO_2eq, 200 €/tCO_2eq, 400 €/tCO_2eq), GHG emissions savings of up to 23% compared to the awarding according to construction cost can be achieved within the 37 scenarios considered. In addition to the prerequisite that the awarding of contracts according to the lowest eLCC must be anchored in the tender documents, the implementation of LCA (calculation of embodied and operational emissions) must also be required, as the GHG emissions of the building scenarios are necessary for the calculation of the external cost. For this purpose, all calculation principles and databases to be used must also be specified in the tender documents (Lützkendorf 2021). It seems necessary to consolidate sustainability assessment experts, i.e., LCA and LCC experts, in order to be able to check the offers correctly. It has to be mentioned that solely the involvement of sustainability assessment experts does not solve the problem, but we are convinced that this measure is a necessary important step to implement and ensure more environmentally friendly procurement of buildings in the future. Similar to LCC implementation, there are only a few studies on the implementation of LCA in current procurement practices (Francart et al. 2019; Vidal and Sánchez-Pantoja 2019; Fuentes-Bargues et al. 2017; Ng 2015; Du et al. 2014). This is also confirmed by a recent study commissioned by the European Commission, which analyzed 207 tenders and 16 court cases for the application of LCA-based criteria in the procurement process (Schreiber et al. 2021). Moreover, the literature identified obstacles to its implementation. These obstacles were classified into five categories, (i) methodological obstacles, (ii) organizational obstacles, (iii) economic obstacles, (iv) legal obstacles, and (v) political obstacles, in a review article on LCA implementation in procurement of buildings (Scherz et al. 2022a).

Finally, a shadow price must also be determined for the calculation of the eLCC. In this context, the literature discusses starting values for carbon prices or ranges for carbon prices (Rennert et al. 2022; Arendt et al. 2020; Schneider-Marin and Lang 2020; De Nocker and Debacker 2017; Allacker and De Nocker 2012). In this context, particular attention must be paid to a precise use of terms within the carbon pricing instruments (carbon tax, ETS, crediting mechanism, RBCF, shadow price, internal carbon fee) and to the avoidance of double-accounting. As mentioned in the introduction section the eLCC is based on shadow prices. For instance, the World Bank Group has signaled intentions to implement shadow prices, in consistence with the high-level commission recommendations on carbon prices, on relevant investment projects (Carbon Pricing Leadership Coalition 2018). Additionally, besides to the shadow prices within the LCA-based bonus/malus system, a RBCF

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approach is applied. The shadow prices and the RBCF carbon prices assumed in this study are based on literature values (CCCA-Experten 2020) as well as on the European Union average value of carbon prices (The World Bank 2021).

The results show that the application of the defined shadow price range and RBCF carbon price range lead to a change in the award decision. A detailed examination by calculating the environmental break-even points shows that these values fit well into the existing literature (Rennert et al. 2022; The World Bank 2021). Although the defined shadow prices also lead to a change in the scenarios when allocated according to eLCC, they are in the upper range compared to the literature values. For this reason, the LCA-based bonus/malus system was developed. By combining this RBCF approach, i.e., the GHG emissions bonus/malus, and the eLCC, an approach to calculate so-called PCC scenarios is demonstrated. A bonus (lower GHG emissions than the mean value of all GHG emissions of the submitted scenarios) is deducted, or a malus (higher GHG emissions than the mean value of all GHG emissions of the submitted scenarios) is added to the eLCC. The same GHG emissions reduction, i.e., 12% or 25%, can be achieved with the awarding according to PCC scenarios, but at a lower shadow price and RBCF carbon price, i.e., at 26 €/tCO_2eq and 277 €/tCO_2eq.

The importance of this research direction is also underlined by the development of the Carbon Risk Real Estate Monitor (CRREM). This tool assists real estate owners in reducing operational emissions from existing properties (Wein et al. 2022). Similar to the concept of the LCA-based bonus-malus system, the idea of CREEM is to provide Paris-compatible pathways to achieving our climate goals. While CREEM focuses on the current building stock and takes into account operational emissions, the proposed LCA-based bonus/malus system aims to encourage more environmentally friendly procurement decisions for new buildings based on a whole life cycle perspective, i.e., embodied and operational emissions. However, it can also be used for tendering and awarding refurbishment projects.

4.1 Critical remarks

Awarding contracts according to conventional LCC, eLCC, or PCC scenarios requires mandatory consideration and implementation of LCA and LCC in the tendering and awarding phase of buildings. However, the use of these two methods at this early stage of projects involves a number of obstacles. On the side of the awarding authorities, the complete and transparent specification of all requirements for the implementation of LCA and LCC in the tender documents has to be stated. Furthermore, it is necessary to ensure the correct verification of the offers in order to guarantee the comparability of the offers. In this context, and also for the preparation of the tender documents, sustainability assessment experts will have to be consulted in the future. While the choice of a functional performance specification allows bidders to include their own innovative ideas into projects, the choice of a constructive performance specification must allow alternative offers in order to generate GHG emissions reduction potential. On the bidder's side, the additional time and cost involved in preparing a bid have to be mentioned. In order to remain marketable and competitive in the adapted tendering and awarding process, know-how in the field of sustainability assessment must be generated.

Since the implementation of LCA and LCC in the tendering and awarding process is currently not mandatory, in this context, the next step towards Paris-compatible buildings must first be taken by the awarding authorities as well as the policy-makers. However, the application of the LCA-based bonus/malus system and thus the awarding of contracts according to PCC scenarios show promising GHG emissions reduction potential and thus represent an innovative and sustainable framework for an adapted procurement process. Due to a lack of data, i.e., emission pathways for different building types to achieve the Paris climate goals, it was not possible to show a detailed distance-to-target deviation in terms of GHG emissions from residential buildings. Therefore, the calculated PCC scenarios are only a first approach to determine future cost scenarios for Paris-compatible buildings and for the achievement of the Paris climate targets. To determine real PCC scenarios, detailed shadow prices and RBCF carbon prices based on specific emission pathways for individual building typologies must be implemented in the LCA-based bonus/malus system. A recent study modelled the embodied carbon cost of the domestic building stock and investigated carbon reduction interventions (Drewniok et al. 2023).

With regard to the different building typologies, it should be emphasized that the developed LCA-based bonus/malus system and thus the awarding according to eLCC or PCC scenarios can be used for all building typologies. In this study, we validated the LCA-based bonus/malus system only on a single-family house. However, the prerequisite for its application is that the Federal Procurement Act is used as the basis for the tendering and awarding process, and the willingness to pay for the GHG emissions based on shadow prices and RBCF carbon prices. For other building typologies, it is expected that the identified GHG emissions savings potentials, as well as the environmental break-even points, will be different than in the case study examined. Awarding based on PCC scenarios is particularly useful for awarding authorities that are also users of the buildings, as external cost based on GHG emissions are taken into account. It is also worth mentioning that prices for awarding authorities may increase. In this context, the investor-user dilemma should be pointed out. If the investor is not the user, the investor

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will endeavor to seek an award based on construction cost. If the investor is also the user, in the case study under consideration, there are no additional cost when awarding according to conventional LCC. Although the conventional LCC are 20% higher than the construction cost, this cost difference cannot be described as an additional cost, since the awarding according to construction cost does not take into account the operational cost over 50 years. When applying eLCC, the additional cost amount to 2 or 20% compared to awarding according to conventional LCC. When applying the LCA-based bonus/malus system and awarding according to PCC scenarios, the additional cost compared to conventional LCC amount to between 1 and 11%. However, even if the user is not the awarding authority, the abatement cost for more environmentally friendly buildings should be borne by both the awarding authority and the users, and not by the rest of society. Regarding the production and construction phase of buildings, it does not matter whether prefabricated buildings elements or on-site construction is used for the application of the LCA-based bonus/malus system. Emissions from both prefabricated and on-site construction must be taken into account. In the case of prefabricated building elements, this can be done with environmental product declarations (EPDs), which include the production process, or bidders who offer prefabricated building elements must evaluate their production processes accordingly within the offer.

Additionally, the implementation of the climate fund needs to be examined in detail. In particular, the start of the climate fund needs to be discussed, as there needs to be a starting amount before the climate fund is further filled with the GHG emission malus from projects.

Finally, it should be mentioned that when awarding contracts according to conventional LCC, eLCC, or PCC scenarios, only price has to be specified as an award criterion, which may be advantageous in future award procedures, since in practice the procurement of construction services is still based on price. Nevertheless, it is not our intention to limit the award of contracts to price alone. It is also possible to define and weight other award criteria in addition to price. For example, when awarding contracts according to conventional LCC, eLCC, or PCC scenarios, other award criteria can also be used, such as professional qualification of key personnel, optimization of the construction and/or operating phase, employees over 50 years of age and employment of trainees, reduction of transport kilometers and truck transports, and extension of warranty.

4.2 Limitations

Although the application of the LCA-based bonus/malus system and thus the calculation of PCC scenarios area feasible for all building types, it was only validated on the basis of the underlying case study. This means that it has currently only been applied to residential buildings and further investigation of multi-storey residential buildings, as well as non-residential buildings, is needed. This is of particular importance because private awarding authorities can currently use the process model only if they use the Federal Procurement Act as a basis for their contracts. However, in practice, private buyers in general do not use the Federal Procurement Act as a basis for their contracts. Nevertheless, the objective of the study was to validate the developed process model by means of a case study and to investigate how shadow prices and RBCF carbon prices have to be set in order to achieve a change in the awarding process. Since 37 tender variants were developed for the single-family house in the course of a research project, this case study corresponds to reality from the perspective of the practical process flow, which allowed the validation of the process model in the most appropriate way.

Additional strategies and emerging technologies, which could further reduce the GHG emissions towards Paris-compatible buildings, such as carbon capture and storage or fast-growing bio-based materials (Alaux et al. 2022), could also be included in future calculations.

Further limitations arise from a methodological point of view. The PCC scenarios consist of the eLCC and the LCA-based bonus/malus system. eLCC includes next to construction cost, operation cost, maintenance cost and end-of-life cost, and only external cost. Other cost types like non-construction cost and income, as suggested within WLC or other external cost as proposed within societal LCC, are not considered. In this context firstly, this study only considers external cost within the eLCC. Secondly, the external cost do not include all environmental indicators, but only the environmental indicator GWP in t/CO_2eq which is monetized with shadow prices. Thirdly, conventional LCC and eLCC calculations are based on assumed calculation parameters such as inflation rate, interest rate, price increase rates, or energy prices. These calculation parameters are dynamic over time and always subject to uncertainties. Especially in times of crisis, such as the COVID crisis and the Ukraine-Russia conflict, the parameters deviate strongly from literature values and expected developments. In this study, calculation parameters were assumed that were common before the aforementioned crises. Sensitivity and uncertainty analyses (e.g., with Monte Carlo Simulations) would provide even more detailed insights into the results and would minimize uncertainties in decision-making. However, in this study, we chose only fixed initial values for the calculation parameters within the conducted assessments and did not vary them in increments within a defined range.

5 Conclusions

Rising GHG emissions keep forcing climate change and are increasingly turning into a significant global challenge. For global warming to be kept below 1.5 °C by 2050, the

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amount of remaining carbon budget globally is estimated to be 400 billion tons of CO_2 (IPCC 2022). Contributing 37% of global GHG emissions, one of the leading emitters is the construction industry (UNEP 2021).

This negative trend is reinforced by increasing urbanization. Due to the increasing population in cities, about 60% of the buildings worldwide have to be built first. This implementation of new buildings must therefore be tendered and awarded, making an adaptation of the building procurement process an important lever for GHG emissions reduction. In this study, we therefore adapted the tendering and awarding process and analyzed the differences in the award decisions based on the awarding according to conventional LCC, eLCC, and PCC scenarios. By applying a developed LCA-based bonus/malus system, the applied level of shadow prices and RBCF carbon price was reduced. Finally, based on the changes in the award decisions, enhancement strategies for residential buildings were derived to contribute to the achievement of the Paris goals.

In summary, the findings show that an award based on conventional LCC results in a reduction of GHG emissions. This reduction in GHG emissions can be further increased by awarding contracts based on eLCC. The calculation of environmental break-even points has shown that the shadow prices used in the eLCC are too high compared to the literature. For this reason, the LCA-based bonus/malus system was applied to calculate PCC scenarios. By using PCC scenarios, the same GHG emissions reduction can be achieved as with the eLCC, but at a significantly lower shadow price and RBCF carbon price.

From a technical point of view, using wood-concrete and wood-frame construction instead of brick as construction material seems to have the most potential to reduce GHG emissions, among the residential building scenarios. In addition, it shows that the installation of heat pumps instead of pellet heating brings another environmental advantage.

In conclusion, it must be mentioned that the results of our study are of great importance for the further reduction of GHG emissions in the construction industry. Based on the case study under consideration, we show a GHG emissions reduction of 12 to 42% for residential buildings by adapting the procurement process. Taking into account the huge amount of newly constructed buildings, this reduction can be multiplied by a factor of several times.

Especially for awarding authorities, which can take an exemplary role in a first step, the application of eLCC and the LCA-based bonus/malus system is a good possibility to contribute to the achievement of the Paris climate goals. In a second step, the theoretical framework of the LCA-based bonus/malus system and the validation based on the case study will make policy-makers aware of necessary adjustments in the current procurement practice of buildings.

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Data availability All data generated or analyzed during this study are included in this published article and its Supplementary information files.

Declarations

Conflict of interest The authors declare no competing interests.

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Thesis publication 5

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A hierarchical reference-based know-why model for design support of sustainable building envelopes

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ABSTRACT

In current complex building designs, sustainability assessments are often performed after project completion, with limited impact on building performance which results in missed goals in terms of quality, cost, and time. We address this problem by proposing a hierarchical reference-based know-why model to answer the research question "what is a suitable decision support model to successfully integrate the sustainability requirements in the early design phase of buildings?". The model presents a process that incorporates a life-cycle perspective and calculates design alternatives based on a defined reference and the DGNB building certification system. The results show that criteria synergies and trade-offs can be identified, leading to improved design by engineers and better building performance. Our findings pave the way for full integration of the model into building information modeling, combined with artificial intelligence. This can help manage the complexity of the sustainable design process on the path to carbon-neutral buildings.

1. Introduction

Greenhouse gas emissions and the associated global warming caused by humankind has been changing life on our planet. Pollution, deforestation, overusing fossil fuels and other changes all have been triggering climate change which necessitates swift response and taking proper measures in all economic sectors to reduce the negative impact on the environment. Objectives from all sustainability dimensions are now increasingly entering the policy realm [1,2]. According to Rockström [3], four out of seven planetary boundaries have already been exceeded. In addition to the areas of biodiversity loss, nitrogen cycle and land use, the limit exceedances also concern climate change [4].

One of the sectors that is largely responsible for these negative environmental trends is the construction sector [5–7]. The construction sector consumes 40 to 75% of the total value of materials mined worldwide [8]. In addition to the enormous amount of extracted materials, the construction sector is also responsible for consuming 25% of the global water [9]. In terms of emissions, the construction sector is accountable for emitting 39% of global greenhouse gas emissions [10]. With the 2030 Climate Target Plan, the European Union aims to reduce greenhouse gases by 55% compared to the amount in 1990. To achieve this, greenhouse gas emissions in the construction sector must decrease by 80 to 90%, and building-related energy consumption must decrease by 14% [11]. Based on these alarming numbers, sustainability assessment of buildings is becoming increasingly important.

In the context of reducing the environmental impact of buildings and increasing the building quality, the design phase of buildings is crucial due to the maximum flexibility in terms of considering and implementing sustainability aspects [12,13]. However, it is not practicable to design based on repetitive procedures and processes because of the unique features of each building. Additionally, the design process is emphasized by sustainability requirements due to the overall complexity inherent to each building, given by structural, static, and building physics constraints.

Back in 2008, ISO 15392 established a uniform understanding of sustainability for the construction sector [14]. Progressive work at the European level has created harmonized standards and numerous normative and voluntary instruments to promote the implementation of sustainable construction [15]. The European framework of CEN/TC 350 states that in addition to the three sustainability dimensions, i.e., environmental dimension, economic dimension, and social dimension [16], also the functional and technical qualities of buildings must be taken into account in sustainability assessments [17–20]. In order to be able to evaluate these multitude aspects in terms of sustainability, numerous

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building certification systems have been established on the market over the last two decades. Many of these building certification systems consequently include complete sets of criteria for sustainability assessment, although with different concentration.

The problem thereby lies in the circumstance that sustainability assessments are often carried out after project completion, where there is limited possibility to influence the building performance and the sustainability assessment result within building certification systems. In order to perform a sustainability assessment in the design phase of buildings, the criteria as well as their interdependencies must be considered. In this regard, various systemic approaches in relation to sustainability criteria interactions in the construction sector are discussed in [21–26]. However, due to excessively complicated interdependencies among factors, the application of systems thinking methods in the design phase of buildings is not straightforward [27].

In this context, Building Information Modeling (BIM) as one of the main streams of the Industry 4.0 era is also at the center of the transformation of the planning process. The implementation of sustainability aspects in BIM has become increasingly important in research in recent years [28,29]. Particularly in the design phase, BIM already has offered the possibility to implement, in addition to 3D modeling, the time scheduling (4D), the cost estimation (5D) as well as aspects of sustainability assessment (6D) [28,30]. Design tasks that can be integrated in BIM include energy performance analyses, CO_2 emission analysis, solar and light simulation, thermal comfort analysis and waste management [29,31]. Due to the growing impacts of climate change, implementation options for Life Cycle Assessment (LCA) in BIM are being promoted [32–34]. In addition to the ecological assessment of buildings, the economic assessment of buildings is also being integrated into BIM by means of the Life Cycle Costing (LCC) method [35,36]. Initial approaches that address the problem of systemic interactions of different sustainability requirements are already analyzing different building designs and their interdependencies in terms of different sustainability criteria, e.g., LCA and LCC [37,38].

Nevertheless, the implementation of tools or methods for a holistic building design in the design phase is indispensable. If a parameter is changed in a system with four or more interacting parameters, its effects on the system cannot be perceived manually [39]. Due to this, the way of thinking in simple logical contexts often leads to overlooking medium or long-term effects on the immediate environment. Future generations are endangered, when the objectives of sustainable development cannot be reached [40]. In order to deal with complex systems and the associated inherent dynamics of the systems, a networked way of thinking is necessary [41].

The implementation of sustainable buildings is a multidimensional concept that is gaining relevance in all areas of society [42]. Barbier [43] states that sustainable development involves the simultaneous maximization of environmental, economic, and social goals. However, as Munda [44] has shown, it is generally not possible to maximize different goals simultaneously. Therefore, a compromise between the different objectives must be found, which can be achieved by applying a proper Multiple Criteria Decision Making (MCDM) method. MCDM methods have been largely used in the construction industry in a variety of practical topics and contexts. These include, for example, the selection of construction materials [45,46], the selection of construction equipment [47–49] and risks of construction projects [50]. In this context, MCDM methods were also addressed in relation to the evaluation of green construction suppliers in designing processes of construction supply chains [51]. Within the environmental topics, MCDM methods have been applied, for example, in waste management, energy management [52], wastewater treatment, water quality, or air quality. For a review of MCDM methods applied in the (sustainable) construction industry, see the review articles by [55,57]. Other examples include transportation and logistics in general [7,53,54], but also transportation and logistics considering environmental issues [56,58].

The goal of the article is to support the consideration of sustainability aspects in the early design phase of buildings by developing a suitable decision support model. In this study, we take advantage of a MCDM method named hierarchical decision modeling (HDM) and combine it with the principles of the know-why method which is a systems thinking methodology. The proposed hybrid model (i.e., hierarchical reference-based know-why model) incorporates the advantages of a classic MCDM approach in dealing with complex set of goals, alternatives and criteria and a systemic approach to handle the relationships between them.

The rest of this article is organized as follows. In Section 2, materials and methods which are employed in our research are discussed. In Section 3, the proposed hierarchical reference-based know-why model is explained. Results are presented in Section 4 and findings are discussed in discussion section (i.e., Section 5), followed by the conclusions, limitations, and future research directions in Section 6.

2. Materials and methods

2.1. Research framework

With the aim to develop a decision model based on given sustainability requirements and considering the systemic interactions, a research question is developed as: *what is a suitable decision support model to successfully integrate the sustainability requirements in the early design phase of buildings?*. To answer the research question, three approaches have been applied in our proposed model including (i) building certification systems, (ii) MCDM methods and (iii) systems thinking approaches. In contrast to BIM, the hierarchical reference-based know-why model is characterized by the unique selling point that it can be filled with qualitative or semi-quantitative data, thus reducing the time-consuming data acquisition in the early design phase of sustainable buildings. As shown in Fig. 1, the hierarchical reference-based know-why model lies in the intersection of these three approaches and docks with the method of BIM, as it could also be fully integrated into BIM in future research.

2.2. Building certification systems

Frameworks for assessing buildings in terms of sustainability have been established since the last decade of the 20th century [59,60] leading up to 600 assessment methods now available [61]. The range of sustainability issues that are addressed by these methods is diverse and ranges from a single topic, such as energy efficiency, to a broad spectrum of topics that belong to all three pillars of sustainability. Building certification systems are considered objective and contain clear comparative tools for a holistic sustainability assessment of a building. Moreover, they are developed and structured in a way that results of the building assessment are transparent and are followed by a certificate suitable for the use in the building market. The sustainability criteria are, however, assigned and weighted differently in various systems [62]. Because of the huge amount of sustainability criteria in building certification systems, the majority of users and planners lack knowledge about their effects on the certification result and therefore on the quality of the building. For this reason, the systemic interactions among the criteria of building certification are frequently underestimated [63–66] and stakeholders need a building management tool based on sustainability criteria [67].

From the comparison of several building certification systems, we can state that the DGNB criteria set is an advanced certification system of the so-called 2nd generation [23] and in line with the CEN/TC 350 requirements [17–20]. Due to this and due to the certification of the case study according to the building certification system DGNB, it was applied for further model development [68].

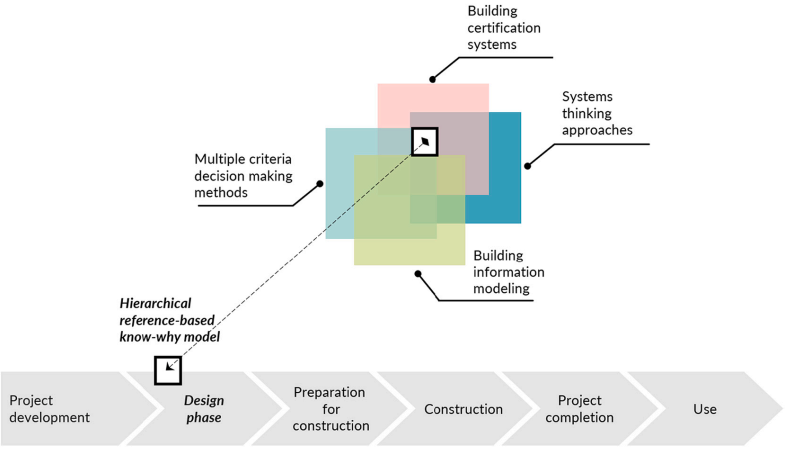

Fig. 1. Research framework.

2.3. Hierarchical decision modeling (HDM)

HDM was introduced by Chen and Kocaoglu [69] as an MCDM method. HDM helps decompose problems into hierarchical levels in order to deal with multiple decision layers which are common in complex decision-making problems [70]. HDM represents the problem in a hierarchical structure by providing a visual understanding for decision makers to understand which criteria or sub-criteria can influence the objective or mission [71]. A mission-objective-goal-strategy-action model (MOGSA) including five decision levels was also proposed as the classic structure in the literature [72]. However, the structure can vary based on specific requirements in each use case [71]. For instance, a three-level HDM (mission, perspectives, factors) is depicted in Fig. 2.

HDM has been applied in various decision-making contexts such as technology transfer in the energy sector [56], laptop purchase problem [73], stadium site selection [74], solar photovoltaic technologies [75] or health technology assessment [76].

The mathematical background of a three-level HDM (mission, perspectives, and factors) as shown in Fig. 2 is presented in Eq. (1) [54,56].

$$V_{n,j} = \sum_{n=1}^{N} \sum_{j=1}^{M} w_n C_{n,j} \tag{1}$$

where,

$V_{n,\,j}$ = relative value of the jth factor under the nth perspective.
w_n = relative priority of the nth perspective.
$C_{n,\,j}$ = relative contribution of the jth factor under the nth perspective.

2.4. Know-why model

Systems thinking has become increasingly important in recent years. Various systemic approaches in relation to sustainability criteria interactions in the construction industry are discussed in [25,77–79].

While Zavadskas et al. [66] emphasizes the importance for building management tools based on sustainability criteria for stakeholders in the design phase of buildings in general, Neumann [27] go in more detail and argue that the reason why it has been quite complicated and tedious to analyze these individual cause-effect relationships so far seems to be mainly because the tools and methods needed to do so have been far too complicated, why a further development of simple tools, but also tools for qualitative assessment is necessary.

Qualitative modeling, in contrast to quantitative modeling, requires no specific data, formulas or parameters and does not lead to exact scenarios, which in many cases are not accepted as accurate anyway. Above all, the only rough, qualitative description of interrelationships is much faster. Such a rough weighting of the interrelationships also stands up to scientific criteria. For many challenges of the present and future, we would not be able to fall back on data from the past - therefore, the only remaining option is an investigation based on abductive-logical conclusions, i.e., a consideration of the consequences of an assumption that is valid until it can be refuted. Errors can still occur, if illogical connections are made or decisive factors are not considered at all.

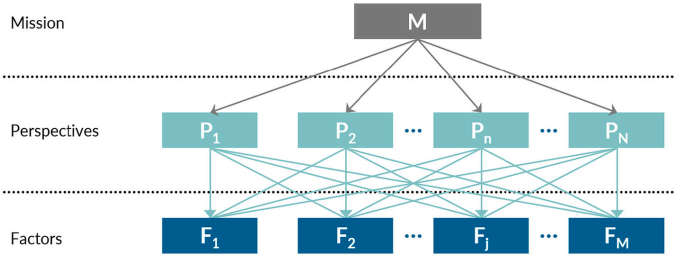

Fig. 2. Three-level HDM.

A method that supports the qualitative (but also quantitative) modeling of complex systems is the know-why method. The know-why method offers a highly practical approach to addressing the complex challenges of business, politics, and personal life. The know-why method simply asks you to consider the evolutionary pattern of success by answering the four know-why questions in the course of qualitative or quantitative modeling [27,80]. These four questions are (i) what leads directly to more of it right now?; (ii) what leads directly to less of it right now?; (iii) what might lead directly to more of it in the future?; and (iv) what might directly hinder it in the future?.

These four questions are modified for the proposed hierarchical reference-based know-why model based on the defined reference alternative as follows:

(i) what leads directly to more of it right now compared to the reference alternative?
(ii) what leads directly to less of it right now compared to the reference alternative?
(iii) what might lead directly to more of it in the future compared to the reference alternative?
(iv) what might directly hinder it in the future compared to the reference alternative?

This modification leads planners to being able to answer the know-why questions for alternatives (building envelopes) in the early designing phase based on their experience compared to an already known and unchanging alternative (reference building envelope).

The modification of the know-why questions as well as its application was tested in a research project during the design of building envelopes and used for the development of a sustainable design process (see supplementary materials). Therefore, the term "design" is not only understood as the design of the whole building, but also the design of individual building elements.

3. Hierarchical reference-based know-why model

A combination of building certification systems (in our case DGNB) and HDM can help facilitate the understanding of complex systems by breaking it down to individual interrelated levels. Thus, a hierarchical reference-based know-why model can help identify the most appropriate alternatives based on the building certification system, the hierarchical structure, and by incorporating individual preferences compared to a reference alternative. The proposed model is comprised of the following steps:

Step 1: Identify criteria, sub-criteria, alternatives and the reference alternative.

The façade-relevant certification criteria were identified along with sub-criteria, alternatives and the reference alternative.

Step 1.1. Relevant certification criteria for buildings envelopes.

A total of 17 expert workshops were held with the aim of identifying the influencing certification criteria for assessing different building envelopes. The overall goal of the workshops was to determine the influence of different building envelopes on the façade-relevant certification criteria and therefore, on the certification results. In each of these workshops, it was ensured that at least 6 experts with different professional backgrounds (i.e., structural engineers, thermal engineers, industrial engineers, economic engineers, and sustainability assessment experts) participated in order to guarantee the interdisciplinary constellation.

In the first series of workshops, the façade-relevant certification criteria were identified. For this purpose, the certification criteria of the DGNB building certification system were used to identify criteria which were "façade-relevant" or criteria for which the building envelope had an influence on the sustainability assessment at the building level. In the sense of a "top-down" approach, based on the DGNB building certification system, the certification criteria were broken down to the building component level. The analysis has shown that the building component "building envelope" influences a total of 22 out of 38 criteria. In order to be able to depict the influence of building envelopes on the life cycle phases in more detail, the criteria "building life cycle assessment" (ENV1.1) and "life cycle cost" (ECO1.1) were subdivided into three further equally weighted criteria. The criteria ENV1.1 and ECO1.1 address LCA and LCC. These two methods cover and evaluate the entire life cycle of a considered building, a considered building component or a considered building product. In order to evaluate the alternatives in more depth, these two criteria were divided into the production phase (ENV1.1a and ECO1.1a), the use phase (ENV1.1b and ECO1.1b) and the end-of-life phase (ENV1.1c and ECO1.1c). Thus, the 22 identified façade-relevant criteria resulted in 26 criteria, which were used for the expert evaluation. Based on the identified façade-relevant criteria, the sub-criteria were based on the DGNB building certification system (see the appendix).

Step 1.2. Reference alternative.

In the second workshop series the reference alternative was chosen, and other building envelope alternatives were designed. The reference alternative was the case study "Karmeliterhof" (an office building situated in Graz, Austria), which served as the assessment basis for the other alternatives (Table 1).

The six-story office building was designed as a solid construction. Non-load-bearing walls and parapets were made of brick or double-shell plasterboard. The building envelope was composed of a 16 cm thick thermal insulation composite system. The roof construction was made of a warm roof with a roof covering in fiber cement. The transparent exterior components were made from double glazing. The floor covering composed mainly of industrial parquet, the kitchenettes and sanitary facilities on the individual floors had a ceramic floor covering. The floors of the technical rooms in the cellar had an epoxy coating. Glass walls were also constructed as non-load-bearing dividing walls. The proportion of window area in the building was around 26%. The building was heated via a district heating connection. The heat was emitted by radiators and convectors - with the exception of the entrance hall on the first floor - where heating walls and floor heating are installed. Ventilation of the sanitary facilities was mechanical. There was no controlled ventilation of the office areas. Hot water was supplied centrally for the first floor, while the upper floors were supplied decentrally via undersink storage tanks. The same for the kitchenettes and sanitary facilities on each floor. The shower in the cellar was centrally supplied. The building also had a multifunctional room, which was equipped with air conditioning.

Step 1.3. Development of alternatives.

In total, 13 further alternatives were designed with different properties, in which, in addition to the construction structure, the energy generation with solar and/or photovoltaic, the heating and/or cooling possibilities of the building envelope typologies and combination of these were considered. The designed building envelope alternatives are shown in Table 2.

Step 2: Decompose the problem into a hierarchy.

The problem can be decomposed into a few levels in order to make the problem more comprehensible as such a four-level HDM is proposed

Table 1
Case study parameter Karmeliterhof in Graz, Austria (reference alternative).

Characteristics	Measured value
Building type	Office building
Gross floor area	2300 m^2
Stories	5 + 1
Outer wall construction	Reinforced concrete, brick wall, thermal insulation system
Energy efficiency class	B (39 kW/m^2*a)
Surface-volume ratio	0.21 [m-1]
Heat generation	District heating
LEK value	33 [−]
Average U-Value	0.565 [W/ m^2*K]

Table 2
Description of building envelope typologies.

Alternatives	Building envelope typology	Construction	Energy generation	Conditioning
R01	ETICS[1]	Massive wall construction with window bands Plaster – Brick (25 cm) – EPS[2] (16 cm) - Plaster	–	–
A01	ETICS[1]	Massive wall construction with window bands Plaster – Brick (17 cm) – EPS[2] (16 cm) - Plaster	–	–
A02	M&T[3]	Curtain wall (Skeleton construction)	–	–
A03	M&T[3]	Curtain wall (Skeleton construction)	No element-integrated energy generation (façade collectors)	–
A04	M&T[3]	Curtain wall (Skeleton construction)	Energy generation (photovoltaic modules)	–
A05	M&T[3]	Curtain wall (Skeleton construction)	–	Room conditioning (heating and cooling system – building element activation)
A06	M&T[3]	Curtain wall (Skeleton construction)	No element-integrated energy generation (façade collectors)	Room conditioning (heating and cooling system – building element activation)
A07	M&T[3]	Curtain wall (Skeleton construction)	Energy generation (photovoltaic modules)	Room conditioning (heating and cooling system – building element activation)
A08	SP[4]	Element façade with polyurethane insulation Aluminium sheet – PU[5] – Aluminium sheet	–	–
A09	SP[4]	Element façade with polyurethane insulation Aluminium sheet – PU[5] – Aluminium sheet	Element-integrated energy generation (no glass plate)	–
A10	SP[4]	Element façade with polyurethane insulation Aluminium sheet – PU[5] – Aluminium sheet	Energy generation (glued photovoltaic panel)	–
A11	SP[4]	Element façade with polyurethane insulation Aluminium sheet – PU[5] – Aluminium sheet	–	Room conditioning (heating and cooling system – SP panel
A12	SP[4]	Element façade with polyurethane insulation Aluminium sheet – PU[5] – Aluminium sheet	Element-integrated energy generation (no glass plate)	Room conditioning (heating and cooling system – SP panel
A13	SP[4]	Element façade with polyurethane insulation Aluminium sheet – PU[5] – Aluminium sheet	Energy generation (glued photovoltaic panel)	Room conditioning (heating and cooling system – SP panel

[1] External thermal insulation composite system.
[2] Expanded polystyrene.
[3] Mullion and transom.
[4] Sandwich panel.
[5] Polyurethane.

in this study (objective, criteria, sub-criteria, alternatives). Table 3 lists the hierarchical characteristics of the reference-based know-why model.

The proposed model reflects the structure of a four-level HDM (objective, criteria, sub-criteria, and alternatives). It is possible to take individual stakeholders' preferences into account to obtain weights of sub-criteria. For a comparative presentation of results, two scenarios were defined. Scenario A reflects the weighting of the DGNB building certification system. This means that the weighting of the building certification system remains unchanged and thus the alternatives are ranked based on the probability of achieving the highest certification result to the lowest certification result.

Scenario B represents a randomly selected scenario, where the individual criteria were specified based on an individual stakeholder. In this scenario, alternatives are ranked to alternatives that best meet the individual stakeholder's preferences.

One advantage of the model is that an alternative ranking is possible for each level - i.e., for each model element. The hierarchical referenced-based know-why model can place each model's element in the center of the model. Consequently, decision support can be provided for each model's element. Fig. 3 shows the schematic structure of the hierarchical referenced-based know-why model.

Step 3: Construct an assessment matrix using know-why rating.

The contribution of each alternative (j) under each sub-criterion (n) was analyzed individually by each expert (k) on a scale of −2 to +2 ($C_{n,j}^{k}$). Within the expert evaluation, each alternative for the reference alternative was rated as neutral, i.e., with 0.

With the results of the conducted workshops, an assessment matrix was created. This matrix is composed of 14 columns (13 building envelope typologies plus one reference alternative) and 26 rows (22 identified façade-relevant certification sub-criteria plus breakdowns of the two sub-criteria ENV1.1 and ECO1.1). The further workshops were used to evaluate the influence of the defined alternatives on the façade-relevant certification sub-criteria.

Each evaluation of the impact of an alternative on a certification sub-

Table 3
Structure of the hierarchical reference-based know-why model.

Level	General structure of the hierarchical decision-making model	Structure of the model	Explanation
Level 1	Objective	Sustainable building envelope	The overall objective is to design the most sustainable building envelope to increase the probability of a high building certification result already in the design phase
Level 2	Criteria	6 DGNB quality sections	Level 2 contains the six DGNB quality section environmental quality, economic quality, sociocultural and functional quality, technical quality, process quality and site quality.
Level 3	Sub-criteria	38 DGNB sustainability criteria	The six DGNB quality sections are separated by 38 sustainability criteria. These sustainability criteria represent sub-areas of the superordinate quality section and thus simplify the measurability of the sections.
Level 4	Alternatives	Different building envelope typologies	The alternatives present different building envelope typologies. The alternatives differ in the chosen construction method, the used building materials, and the installed technical building equipment. The alternatives are designed and evaluated in expert workshops.

criterion was done individually by each expert on a scale of -2 to $+2$ prior to the workshop. Within the expert evaluation, each façade-relevant certification sub-criteria for the reference alternative were rated as neutral, i.e., with 0. Table 4 shows the linguistic meaning of the evaluation scale.

Step 4: Aggregate opinions of experts.

In order to obtain the aggregation of experts' opinions in terms of the provided ratings in the previous step, Eq. (2) is utilized. Then, consensus procedure was applied to get the aggregated value as a whole number by rounding up/down.

$$S_{n,j} = \frac{C_{n,j}^{k}}{K} \forall k = 1,\dots,K; j = 1,\dots,M; n = 1,\dots,N \tag{2}$$

where,$S_{n,\ j}$= aggregated opinion of experts for the contribution of jth alternative under nth sub-criterion$C_{n,\ j}^{k}$ = relative contribution of the jth alternative under nth sub-criterion by kth expert$K$ = total number of experts.

The review of all data was carried out in the course of the expert workshops. This procedure ensured that no errors were incorporated into the hierarchical reference-based know-why model during the assessment and the aggregation of the data.

Step 5: Compute weights of sub-criteria (W_n): under scenarios A and B.

Next to the weighting for the six DGNB quality sections and their 38 sustainability criteria based on the DGNB building certification system, it is possible to set individual stakeholder preferences for the sub-criteria in the model. Two scenarios (i.e., A and B) are defined. Scenario A that is DGNB criteria weighting unchanged. Scenario B is DGNB criteria weighting changed based on individual stakeholder preferences.

We can look at the DGNB based weighting (scenario A), meaning that the given DGNB weighting is multiplied by 1 (100%) and therefore not changed. Or the DGNB weighting can be changed via the individual preferences, then the DGNB sub-criteria weighting is e.g., multiplied by 0%, 33%, 66% or 100%.

The mathematical adaption to calculate weights of each sub-criterion (W_n) including individual stakeholder preferences as shown in Table 5 is presented in Eq. (3). $W_{n,\ l}$ can be computed considering weights presented in the Appendix by multiplying weights in Tables 8–9 (Appendix)

$$W_n = p_n^A p_n^B W_{n,l} \forall n = 1,\dots,N; \forall l = 1,\dots,L \tag{3}$$

where,

$W_{n,\ l}$ =relative weight of the nth sub-criterion under the lth criterion.

p_n^A= relative priority of the nth sub-criterion (scenario A).

p_n^B= individual stakeholder preferences-relative priority of the nth sub-criterion (scenario B).

Meaning that each sub-criterion can be multiplied by other values in scenario B (Table 6). The weighting of the applied DGNB building certification system (scheme: office and administration buildings) is provided in the appendix.

Step 6: Calculate final value of alternatives.

At this step, the final value of each alternative (V_j) is calculated using Eq. (4).

$$V_j = \frac{\sum_{n=1}^{N} W_n S_{n,j}}{N} \forall \text{j} = 1,\dots,\text{M} \tag{4}$$

where,

W_n = relative weight of the nth sub-criterion obtained in previous step.

N = total number of sub-criteria.

4. Results

In this section, output possibilities of the hierarchical reference-based know-why model are presented. The developed model can pursue two main scenarios: (A) building certification system-compliant planning and (B) individual stakeholder preferences-compliant planning. Combinations of the output possibilities in the know-why model are feasible.

4.1. Evaluation matrix of alternatives

The results of the model are based on the expert evaluation (6 experts) as explained in step 4 in Section 3. These were compared with the reference alternative and evaluated by using the suggested rating scale. The reference alternative was given a score of zero for all 26 sub-criteria. With respect to the criterion being evaluated, better alternatives compared to the reference alternative were given a score of $+1$ or $+ 2$ and worse alternatives compared to the reference alternative were given a score of -1 or $- 2$. Alternatives that have the same impact as the reference alternative were evaluated as zero. Table 7 shows the evaluation matrix for the 26 criteria and the 13 alternatives.

4.2. Building certification system-compliant planning (scenario a)

The know-why model can center each element of the model and thus provide a decision support for any element within the model. Fig. 4 shows the results of the model element of level 1, i.e., the question of the most sustainable building envelope including all six DGNB quality sections. The results are based on the specified weightings from the DGNB building certification system and the expert assessments. The value of each alternative (V_j) of the x-axis are calculated using the calculation methods within the hierarchical decision model and know-why model and is calculated using Eq. (4). In linguistic terms, a positive value

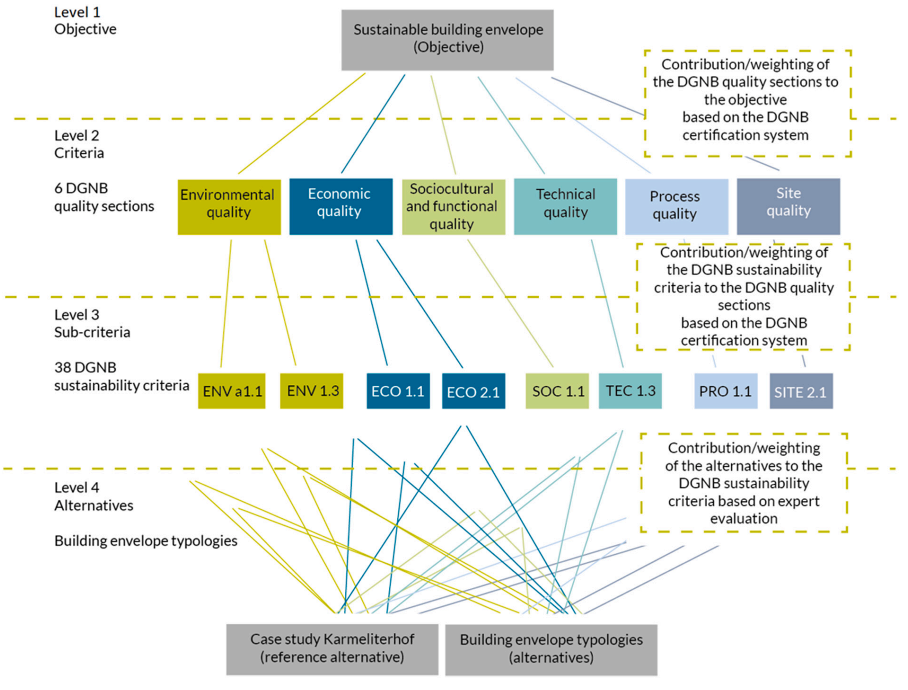

Fig. 3. Structure of the hierarchical reference-based know-why model.

Table 4
The rating scale.

Score	Linguistic meaning
−2	The impact of the assessed building envelope typology has a "high" potential for trade-offs within the observed certification sub-criterion compared to the impact on the reference alternative.
−1	The impact of the assessed building envelope typology has a "medium" potential for trade-offs within the observed certification sub-criterion compared to the impact on the reference alternative.
0	The impact of the assessed building envelope typology has the same impact on the observed certification sub-criterion as the reference alternative.
+1	The impact of the assessed building envelope typology has a "medium" potential for synergies within the observed certification sub-criterion compared to the impact on the reference alternative.
+2	The impact of the assessed building envelope typology has a "high" potential for synergies within the observed certification sub-criterion compared to the impact on the reference alternative.

Table 5
Weights determination scale by individual stakeholder preferences (scenario B) [81].

Score	Linguistic meaning
0%	Not at all important
33%	Moderately important
66%	Important
100%	Highly important

means that this alternative is relatively better than the reference alternative. Conversely, a negative value means that this alternative is relatively worse than the reference alternative.

The best certification result can be achieved with the execution of the designed building envelope A12. A12 is a sandwich panel made of aluminium sheets and PU foam filling. In addition, the sandwich panel has an element-integrated energy generation without an additional glass plate. Heating and cooling functions are performed by the integrated technology in the panel. Detailed constructional details of this building envelope can be found in [82–84]. The building envelope with the worst certification result is alternative A03. This building envelope represents a mullion and transom façade. The curtain wall is constructed as skeleton construction. On the outside, façade collectors were installed for thermal energy generation. In this context, alternative A01, which represents the minimum standard according to Austrian construction guidelines (OIB guidelines), achieves a higher certification result than alternative A03, meaning that the minimum standard is not the worst construction in each case. However, alternative A01 is still relatively worse than the reference alternative. The load-bearing structure of the minimum standard consists of brick with bonded EPS thermal insulation. The surfaces on the outside and inside are plastered with lime plaster. The building envelope has no integrated technical systems and therefore has no energy generation function and no heating and cooling function.

In addition to the visualization from the holistic point of view (level 1), the individual quality sections of the DGNB building certification system can also be presented. Fig. 5 shows the results for the best alternatives for each DGNB quality section (scenario A).

The quality section "site" is not influenced by the building envelope and is therefore not shown. For the quality sections environmental quality, sociocultural and functional quality, technical quality and process quality the building envelope typology A12 is also the one that best meets the sustainability criteria within each quality section. In the

Table 6
Sub-criteria weighting under two scenarios A and B.

No	Sub-criteria	Description	Scenario A (p_n^A)	Scenario B (p_n^B)
1	ENV[1]1.1	Building life cycle assessment	100%	100%
2	ENV1.2	Local environmental impact	100%	33%
3	ECO[2]1.1	Life cycle cost	100%	100%
4	ECO2.1	Flexibility and adaptability	100%	0%
5	SOC[3]1.1	Thermal comfort	100%	100%
6	SOC1.2	Indoor air quality	100%	66%
7	SOC1.3	Acoustic comfort	100%	33%
8	SOC1.4	Visual comfort	100%	0%
9	SOC1.5	User control	100%	66%
10	SOC1.7	Safety and security	100%	33%
11	TEC[4]1.2	Sound insulation	100%	100%
12	TEC1.3	Quality of the building envelope	100%	66%
13	TEC1.4	User and integration of building technology	100%	33%
14	TEC1.5	Ease of cleaning building components	100%	33%
15	TEC1.6	Ease of recovery and recycling	100%	0%
16	PRO[5]1.1	Comprehensive project brief	100%	66%
17	PRO1.4	Sustainability aspects in tender phase	100%	100%
18	PRO1.5	Documentation for sustainable management	100%	33%
19	PRO2.2	Quality assurance of the construction	100%	66%
20	PRO2.3	Systematic commissioning	100%	100%
21	PRO2.4	User communication	100%	66%
22	PRO2.5	FM-compliant planning	100%	66%

[1] Environmental quality.
[2] Economic quality.
[3] Sociocultural and functional quality.
[4] Technical quality.
[5] Process quality.

economic quality, however, it is alternative A13. Alternative A13 is a sandwich panel made of aluminium sheets and PU foam. In contrast to A12, however, the energy generation takes place via a bonded photovoltaic panel.

In conclusion the worst building envelope alternatives differ greatly in the respective quality sections. In the environmental quality and in the sociocultural and functional quality the worst building envelope is alternative A04, in the economic quality section and in the technical quality section the worst becomes alternative A06 and in the process quality section alternative A01 has the worst value.

4.3. Individual stakeholder preferences-compliant planning (scenario B)

The results shown in Section 4.2 can also be calculated for arbitrary scenarios with different individual stakeholder preferences. Fig. 6 shows the ranking of building envelopes from a holistic perspective (level 1) based on the criteria weighting of scenario B.

The building envelope that best meets individual stakeholder preferences is alternative A12. Alternative A03 is the building envelope that fails to meet individual preferences the most. The alternatives for the different model elements can also be ranked and presented for scenarios with individual stakeholder preferences. In scenario B the building envelope typology A12 is the best ranked alternative for the environmental quality section, the sociocultural and functional quality sections, and the process quality section. For the economic quality section, the best alternative is A13. For the technical quality section, the reference case is

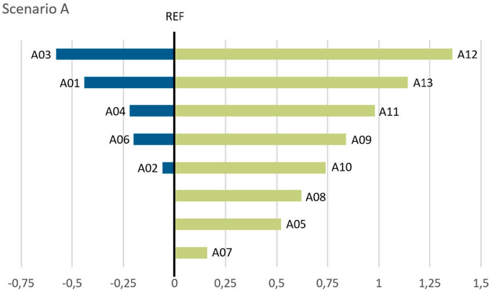

Fig. 4. Best alternatives for building certification system-compliant planning (scenario A).

Table 7
Assessment matrix based on expert judgment.

Sub-criteria	REF	A01	A02	A03	A04	A05	A06	A07	A08	A09	A10	A11	A12	A13
ENV1.1a	0	0	−1	−2	−2	−1	−2	−2	0	1	0	1	1	0
ENV1.1b	0	−1	−1	0	0	1	1	1	1	1	1	1	2	2
ENV1.1c	0	0	1	1	0	1	1	0	2	1	0	2	2	1
ENV1.2	0	−1	0	−1	−1	0	−1	−1	0	−1	−1	0	−1	−1
ECO1.1a	0	1	−1	−2	−1	−1	−2	−2	1	1	1	1	2	2
ECO1.1b	0	−1	−1	0	1	−1	−1	0	1	1	2	−1	0	1
ECO1.1c	0	0	1	1	1	2	1	1	2	2	1	2	2	2
ECO2.1	0	0	1	0	1	1	0	1	1	2	2	2	2	2
SOC1.1	0	−1	−2	−1	−2	1	2	1	−1	0	−1	1	2	1
SOC1.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SOC1.3	0	0	−1	−1	−1	−1	−1	−1	−1	−1	−1	−1	−1	−1
SOC1.4	0	0	1	−1	0	1	−1	0	1	1	1	1	1	1
SOC1.5	0	0	0	0	0	1	1	1	0	0	0	2	2	2
SOC1.7	0	0	−1	−2	−1	−1	−2	−2	−1	−1	−1	−1	−1	−1
TEC1.2	0	−1	−1	−1	−1	−1	−1	−1	−1	−1	−1	−1	−1	−1
TEC1.3	0	0	−1	−1	−1	−1	−1	−1	−1	−1	−1	−1	−1	−1
TEC1.4	0	0	0	0	0	1	1	1	0	0	1	1	2	1
TEC1.5	0	0	2	1	1	2	1	1	2	2	2	2	2	2
TEC1.6	0	1	1	0	1	0	−1	1	2	2	2	2	2	1
PRO1.1	0	−1	1	1	1	1	2	2	1	1	1	1	2	2
PRO1.4	0	−2	0	0	0	1	2	2	1	1	1	1	2	2
PRO1.5	0	−2	1	0	0	1	1	1	1	1	1	1	2	2
PRO2.2	0	−2	0	0	0	0	0	0	0	1	0	1	2	0
PRO2.3	0	0	0	−1	0	−1	−2	−1	0	−1	0	−1	−2	−1
PRO2.4	0	0	0	0	0	−1	−2	−1	0	0	0	−1	−1	−1
PRO2.5	0	−1	1	1	0	2	2	1	1	1	1	2	2	2

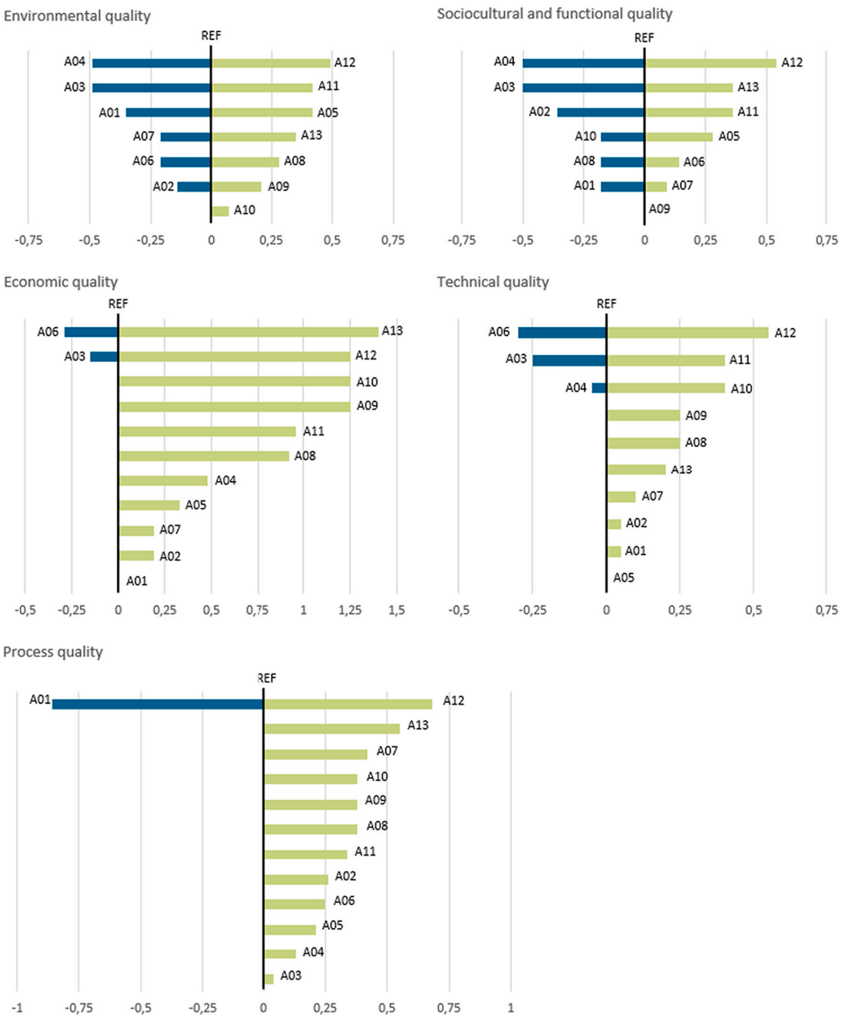

Fig. 5. Best alternatives for the DGNB quality sections (scenario A).

the best alternative to satisfy the stakeholder requirements. In addition to the visualization from the holistic point of view (level 1), the individual quality sections of the DGNB building certification system can also be presented. Fig. 7 shows the results for the best alternatives for each DGNB quality section (scenario B).

5. Discussion

This paper demonstrates the suitability of know-why questions in hierarchical decision making for sustainability improvement processes by combining the DGNB building certification system with a multiple-criteria decision-making method and a systems thinking approach.

The construction sector is an industry that highly interacts with environmental, economic and social dimensions. The concept of sustainability states that there should be a dynamic balance between these dimensions. In this context, the design phase of buildings is the phase in which the greatest influence can be exerted on the building quality and also on the fulfillment of sustainability aspects [85–87]. This early phase is characterized by a high variability of design parameters, often with trade-offs, and subsequently forms an enormous design freedom for planners [88].

Our analytical thinking, which has been shaped for generations, hinders us from taking into account these numerous aspects and, in particular, their interactions and effects in the design phase, which requires the implementation of systemic approaches. This current designing approach leads to striving for area-oriented or goal-oriented

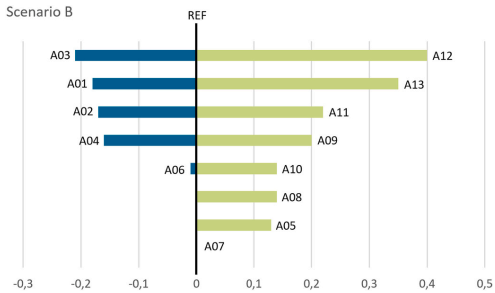

Fig. 6. Best alternatives for stakeholder preferences-compliant planning (scenario B).

designs, forgetting that the sum of the parts is greater than the whole. To counteract these undesirable developments, we propose an early application of the hierarchical reference-based know-why model in the design phase of buildings.

The literature shows that systems thinking in the field of construction industry has been gaining interest in recent years. Different systemic approaches related to interactions between sustainability criteria requirements in buildings are described in [21,23,26,41,65,67,79]. Compared to existing work in the literature, the hierarchical reference-based know-why model takes the next step toward implementing sustainable construction. By mapping the DGNB building certification system as a hierarchical structure and implementing the four know-why questions to evaluate design alternatives, synergies, and trade-offs among set of sustainability requirements can be highlighted.

Unlike the focus of BIM research, which increasingly seeks to extend 3D modeling to include different sustainability aspects [32–34,89,90], the hierarchical reference-based know-why model provides a way to semi-quantitatively assess different design variants and contrast their

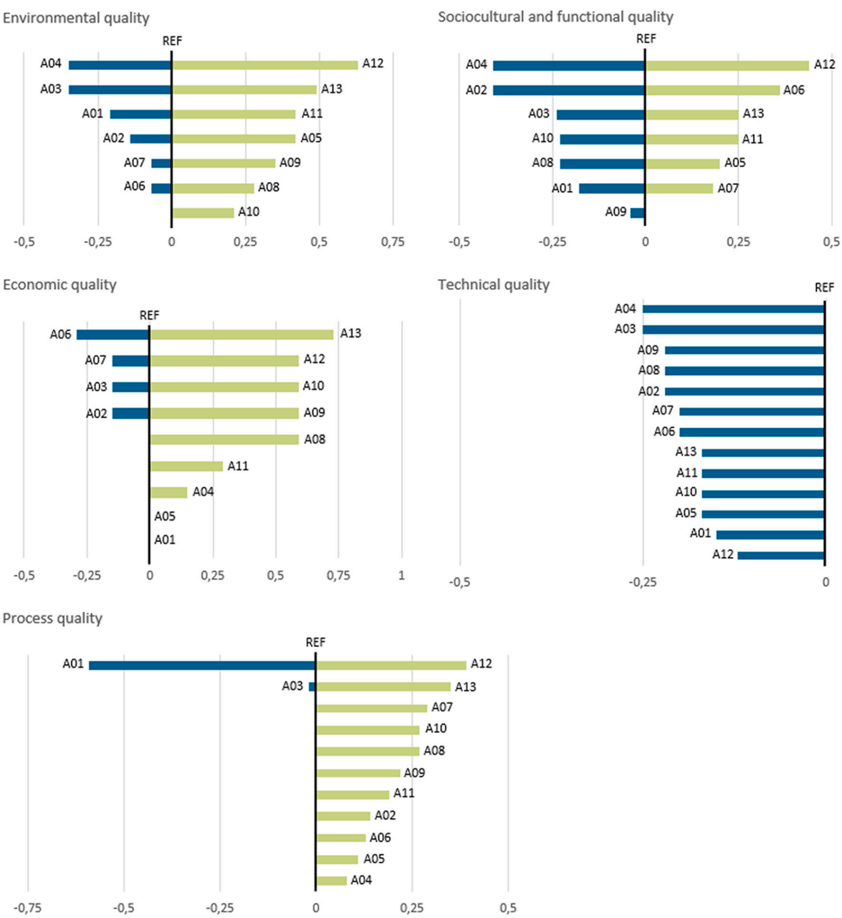

Fig. 7. Best alternatives for the DGNB quality sections (scenario B).

impact on required sustainability goals.

A full implementation of the hierarchical reference-based know-why model in BIM is theoretically possible and not excluded. In this context, interfaces between building certification systems and BIM have already been developed, thus also enabling the evaluation of individual sustainability criteria in BIM [91–94]. However, there is currently no possibility to fully automate all criteria of a building certification system including their interactions as well as the input of individual stakeholder preferences in the BIM design process.

One of the purposes of the hierarchical reference-based know-why model is to support thinking in contexts and thus to ensure that planners are able to holistically consider all requirements for buildings. However, the aim is not to predict an exact value for the contribution of the alternatives, but rather to show, from a more holistic perspective, a positive or negative trend induced by certain design alternatives compared to a well-known reference case and their importance in contributing to the overall project goals.

For the development of the hierarchical reference-based know-why model, the DGNB building certification system was used. It is not the focus of this article to discuss the advantages and disadvantages of different building certification systems. The DGNB certification system was chosen because it is a frequently used performance-based building certification system in Austria, Germany and Switzerland. The DGNB scheme “new building – office” was defined as the scheme, since the reference alternative was a new office building situated in Austria. For building envelopes of other building types, the criteria as well as the criteria weighting may differ depending on the scheme. Modifications to the hierarchical reference-based know-why model for the application to other building elements must be undertaken in the criteria selection process to include the relevant criteria for other building elements. Furthermore, the hierarchical reference-based know-why model in its current form can only be used for the assessment of the building envelope, since 22 of 38 DGNB criteria have been identified as façade -relevant. For the assessment of other building components, the relevant criteria have to be identified and modeled before applying the hierarchical reference-based know-why model. In this context, the model not only can be applied to different building components but also can be applied to a building as a whole. For this purpose, all 38 DGNB criteria must be inserted in the model. In contrast to the current version of the model, the alternatives then no longer represent the building envelopes, but the whole building. Furthermore, a reference building must be defined instead of a reference building envelope. Planners can then use the four know-why questions to evaluate whole buildings in comparison to the defined reference alternative. The presentation of synergies and trade-offs is analogous to the current visualization.

In practice, it may be the case that the “best” design alternative cannot be implemented due to the unique characteristics of buildings. In this case, the focus can be placed on the other proposed alternatives in order to increase the probability of achieving the objectives. In addition to the reference alternative, the current model contains 12 further alternatives that can be used by the planner as a template during the design phase. The aim of the model is not to provide a single building envelope, but to show the advantages and disadvantages of the different alternatives for different DGNB quality sections or criteria. This does not restrict the design freedom of planners, but rather shows possible design variants that can lead to the desired certification result.

An additional re-evaluation in a later planning phase does not have to be carried out. However, the application of the hierarchical reference-based know-why model can also be useful in later design phases since planning variants at a later point in time are more likely to correspond to the construction variant. These design alternatives usually contain detailed information and can therefore be inserted and evaluated in the model in the same way as other alternatives. In addition, a re-evaluation can also be used to perform a target-actual comparison between the design variant in the early planning phase and the design variant in a later planning phase. With these findings, planners can be made aware of the implementation of sustainable building and benefit from this knowledge in future projects.

For the building envelopes currently included in the model, the best certification result is achieved with a sandwich panel construction, consisting of aluminium sheets and polyurethane foam filling with a glued photovoltaic mat on the outer side and an integrated cooling possibility through fluid-filled channels on the inner side. This building envelope typology was designed and developed in a research project at Graz University of Technology, Austria [95][. During the development of the building envelope, an integrated design process was carried out based on the DGNB building certification system. Based on the accompanying sustainability assessment of the building envelope during the design process, iterative changes were made to the structural design, which ultimately ensured the best possible certification result. Details on the construction of the building envelope as well as on the integral and sustainable design process can be found in the supplementary materials. Furthermore, it is also shown that there are building envelopes that achieve a worse certification result than a building envelope that is executed according to the minimum Austrian construction guideline (OIB minimum standards). The results also reveal that in the individual DGNB quality sections or criteria, different building envelopes represent the best alternative. It is worth mentioning that the hierarchical reference-based know-why model can be extended to any additional building envelope. For this purpose, the added alternative must be compared to the reference case by using the presented evaluation scale.

In addition to the goal of achieving the best certification result, the goal was also to make it easier for stakeholders to be involved in the design process. For this purpose, an input mask for individual stakeholder preferences was added to the model. By entering the individual preferences, building envelope typologies can be visualized which fulfill these preferences best or worst. This representation is intended to enable an early basis for discussion between planners and stakeholders in order to think together in the desired direction right from the beginning.

6. Conclusions

The building sector currently contributes to nearly 36% of direct and indirect European Union’s greenhouse gas emissions and 40% of energy consumption. With the 2030 Climate Target Plan, the European Union aims to reduce greenhouse gas emissions by 55% compared to 1990. Consequently, greenhouse gas emissions in the building sector must decrease by 80 to 90%, and building-related energy consumption must also be reduced by 14%. Additionally, achieving the undertaken international, national, or regional climate goals or sustainable development driven agendas such as Agenda 2030, requires that the construction sector continues to evolve toward a net zero carbon-built environment. This transition will not be plausible through merely technological innovations, such as material development, development of energy-efficient technologies, or even the increase of sustainable building standards, but additional developments are necessary in the design process. For this reason, building certification systems have been established in recent decades to promote sustainable construction. However, increased sustainability requirements increase the complexity of the design process and lead to more and more interactions among planning practices. In the design phase, the lack of recognition of these interactions often leads to the overlooking of emerging trade-offs among planning practices and thus to project constraints in terms of cost, time, and quality.

To make this complexity manageable, a systemic approach is necessary. It must be possible to apply this approach in the course of the design phase without major additional effort. Furthermore, an interdisciplinary development of the planning practices as well as a transparent communication of the contents and results must be feasible. We address this problem by answering the research question “what is a suitable decision support model to successfully integrate the sustainability requirements in the early design phase of buildings?”

For this purpose, we proposed a simplified design support tool, called the hierarchical reference-based know-why model, to enable holistic design based on sustainability aspects. For the development of the model, we used the principles of HDM and the know-why method. The know-why method offers a highly practical approach to addressing the complex challenges of business, politics, and personal life by answering the four know-why questions in the course of qualitative or quantitative modeling.

The early identification of the effects of different building or building envelope alternatives will ensure the possibility of the desired building certification level, but also will satisfy the individual preferences of stakeholders at an early stage. In addition to these contributions, the application of the model also reduces the vulnerability to failures due to possible design errors. In our view, these overwhelming advantages are offset only by the additional time and cost required in the design phase. In the current Austrian Fee Scales for Architects and Engineers (HOAI) such expenses are already partially taken into account under the term “special services for the implementation of sustainability aspects”. The required process steps for the effective practical application of a planning tool like the hierarchical reference-based know-why model must be classified in the HOAI in order to define and allocate a payment concept for the additional efforts involved.

The application of the proposed model indicated that different design variants in the form of alternatives can be implemented in a very short period of time. The planner can orientate herself on these suggested alternatives and additionally carry out detailed analyses for individual DGNB quality sections or criteria. Another advantage of the model is that it can be easily and quickly extended to generate a data pool of alternatives. Depending on the desired focus, these data pools can include entire building alternatives, but also different building elements, such as the building envelopes as in this article. For this extension of the data pool, the expert evaluation needs to be performed for new alternatives. This evaluation is performed as described depending on the defined reference alternative. It can be carried out by the responsible planner on her own, based on the experience of past projects, but also by several people from the planning team in the project meetings.

The proposed model is based on the DGNB building certification system and therefore only provides valid results for this certification system. Based on the reference case, we have shown which building envelope typologies achieve the best certification result. The application of the model was tested in the scope of a research project at the Graz University of Technology. Within this project the alternatives were designed by experts and compared to the reference case. The proposed model presents procedural work, including a life-cycle perspective. The model demonstrates value for building designers, planners, and engineers for the early design phase of buildings to improve design processes and to provide an innovative approach to address systemic interactions of planning practices.

In future studies, other similar methods can be compared with our hierarchical reference-based know-why model to increase the validity of the proposed method. Thus, we suppose triangulation can be suitable to enhance the validity of experts’ judgements by applying other similar methods such as best-worst method (BWM) to improve the credibility and reliability of the findings. Furthermore, the proposed model has not been applied in various practical settings which can be undertaken in future research. Ultimately, full integration of the model into building information modeling, combined with artificial intelligence, can help manage the complexity of the design process and further advance the procurement of sustainable buildings on the path to carbon-neutral buildings.

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CRediT authorship contribution statement

Marco Scherz: Conceptualization, Methodology, Software, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization. **Endrit Hoxha:** Validation. **Helmuth Kreiner:** Conceptualization, Methodology, Validation, Supervision, Project administration, Funding acquisition. **Alexander Passer:** Supervision, Funding acquisition. **Amin Vafadarnikjoo:** Methodology, Validation, Visualization.

Declaration of Competing Interest

The authors declare no conflict of interest.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.autcon.2022.104276.

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Appendix B - Additional thesis publications

1. Additional thesis publication 1: **How to make decision-makers aware of sustainable construction?** Kreiner, H., **Scherz, M.**, & Passer, A. (2018) *In R. Caspeele, L. Taerwe, & D. Frangopol (Eds.), Life-Cycle Analysis and Assessment in Civil Engineering: Towards an Integrated Vision - Proceedings of the 6th International Symposium on Life-Cycle Civil Engineering, IALCCE 2018 (pp. 479-485). London.*

2. Additional thesis publication 2: **Visualizing interdependencies among sustainability criteria to support multicriteria decision-making processes in building design. Scherz, M.**, Zunk, B. M., Passer, A., & Kreiner, H. (2018). *In Procedia CIRP, 69, 200-205. https://doi.org/10.1016/j.procir.2017.11.115*

3. Additional thesis publication 3: **Challenges in the achievement of a Net Zero Carbon Built Environment – A systemic approach to support the decision-aiding process in the design stage of buildings. Scherz, M.**, Passer, A., & Kreiner, H. (2020). *In IOP Conference Series: Earth and Environmental Science, 588, 032034. https://doi.org/10.1088/1755-1315/588/3/032034*

4. Additional publication 4: **How to Assess Sustainable Planning Processes of Buildings? A Maturity Assessment Model Approach for Designers**. **Scherz, M.**, Zunk, BM., Steinmann, C., & Kreiner, H. (2022) *In Sustainability, 14(5), 2879. https://doi.org/10.3390/su14052879*

Additional thesis publication 1

Kreiner, H., **Scherz, M.** & Passer, A. (2018). **How to make decision-makers aware of sustainable construction?** In R. Caspeele, L. Taerwe, & D. Frangopol (Eds.), *Life-Cycle Analysis and Assessment in Civil Engineering: Towards an Integrated Vision - Proceedings of the 6th International Symposium on Life-Cycle Civil Engineering, IALCCE 2018*. https://www.taylorfrancis.com/chapters/edit/10.1201/9781315228914-58/make-decision-makers-aware-sustainable-construction-kreiner-scherz-passer

Abstract

Due to multi-criteria requirements in sustainable construction, complexity in decision-making processes is increasing. Limited awareness of systemic effects may lead to imprecise and/or wrong decisions early on in the design stage of building projects. At present, there is a lack of appropriate methods to manage a multi-criteria decision-making process based on a systemic approach. In this article, a methodological approach for the support of decision-making in the early design stage is presented. Based on a grid of sustainability evaluation criteria, a systemic approach is applied and implemented in a three-level process model. The application of the presented process model allows the visualization of possible synergies and trade-offs by implementing sustainable construction. Depending on the expected quality level of the decision-makers' goals, the most crucial life cycle processes can be highlighted additionally. The simplification of complex decision-making by visualizing holistic impacts should lead to increased awareness towards implementing sustainable construction.

Additional thesis publication 2

Scherz, M., Zunk, B.M., Passer, A. & Kreiner, H. (2018). **Visualizing interdependencies among sustainability criteria to support multicriteria decision-making processes in building design.** *Procedia CIRP 69.* `https://doi.org/10.1016/j.procir.2017.11.115`

Abstract

It becomes increasingly challenging to follow decision-making processes while designing sustainable buildings as various sustainability criteria must be operationalized to maintain the optimal integral building performance over its whole life-cycle. Because it is difficult to manage the numerous interdependencies between sustainability criteria as well as their relationships to "traditional" design criteria such as cost, decision-makers are forced to gain in-depth knowledge about the impact of their actions by applying a decision-making process that relies on multiple criteria. In this paper, we introduce a systemic and stepwise management approach based on the literature that can be taken to visualize interdependencies between various building design criteria. This may help decision-makers reduce risk during the management process. Therefore, we present the results of a causal loop investigation. We used causal loop investigations founded on a selection of sustainability evaluation criteria among various building design criteria to identify possible conflicts and identify synergies regarding these sustainability criteria. As a result, we have developed a methodology that - can be used to visualize relevant interdependencies among sustainability criteria in building design, depending on the quality levels of the expected functional and technical equivalents.

Additional thesis publication 3

Scherz, M., Passer, A. & Kreiner, H. (2020). **Challenges in the achievement of a Net Zero Carbon Built Environment – A systemic approach to support the decision-aiding process in the design stage of buildings.** *IOP Conference Series: Earth and Environmental Science 588*. `https://doi.org/10.1088/1755-1315/588/3/032034`

Abstract

By limiting global warming to 2°C, the climate goals set by the United Nations in 2015 (Agenda 2030) will clearly be missed. The shrinking of our GHG budget has shown that the implementation of a weak sustainability concept - i.e. equal consideration of all sustainability dimensions (environmental, economic and social) - is not sufficient to meet the requirements of the Sustainable Development Goals (SDGs). Based on the strong sustainability concept - i.e. focusing on the environmental dimension of sustainability - this article highlights the challenges in the achievement of a Net Zero Carbon Built Environment by the implementation of a systemic design model in the early design stage of buildings. The visualisation of individual planning practices and their systemic behaviour in relation to other planning practices respectively to the SDGs support planners to manage the complexity and to reduce the additional effort within the implementation of sustainability aspects in the early design stage of buildings. Next to the visualisation of the environmental impacts of planning practices, the effects on other SDGs can be highlighted. Furthermore, the planner is supported in the decision-aiding processes in the early design stage. With the application of the systemic design model and the implementation of identified planning practices the contribution to the fulfilment of Agenda 2030 increases.

Additional thesis publication 4

Scherz, M., Zunk, B.M., Steinmann, C. & Kreiner, H. (2022). **How to assess sustainable planning processes of buildings? A maturity assessment model approach for designers.** *Sustainability 14.* https://doi.org/10.3390/su14052879

Abstract

Over the past decades, it has become apparent that increasing demands in the construction industry have repeatedly led to project delays and increased project costs in practice. These demands have increased as a result of international and national action plans that have been developed to achieve the climate target paths and, therefore, the necessary reduction of CO2 emissions in the construction industry. We address this problem by developing a sustainable construction maturity model (SCOMM) to answer the following research question: "What is a holistic quality assurance tool for the early design phase of buildings to monitor (sustainable) planning practices in order to achieve better certification results?". The model includes a self-assessment procedure for the building design process, based on Software Process Improvement and Capability dEtermination (SPiCE) and the German Sustainable Building Council (DGNB) building certification system. The results show that systemic interactions between sustainability criteria can be identified in the early design phase, allowing the quality of planning practices to be evaluated and early project management to be implemented to achieve the best certification results. Our findings will enable clients and users of the construction industry to better manage the complexity of the sustainable design process and avoid undesirable developments in building projects.

Appendix C - Further scientific output

Trummer, P., Ammerer, G., & **Scherz, M.** (2022). Sustainable Consumption and Production in the Extraction and Processing of Raw Materials — Measures Sets for Achieving SDG Target 12.2. Sustainability , 14(17), [10971]. https://doi.org/10.3390/su141710971

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Hoxha, E., **Scherz, M.**, & Passer, A. (2022). Influence of traffic load on the environmental impacts of roads: A1 and A2 highways in Austria. IOP Conference Series: Earth and Environmental Science, 1078(1), [012118]. https://doi.org/10.1088/1755-1315/1078/1/012118

Hopf, B. W., Hoxha, E., **Scherz, M.**, Heichinger, H., Kreiner, H., & Passer, A. (2022). Life cycle assessment of tunnel structures: Assessment of the New Austrian Tunnelling Method using a case study. IOP Conference Series: Earth and Environmental Science, 1078(1), [012117]. https://doi.org/10.1088/1755-1315/1078/1/012117

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Steininger, K., Mayer, J., Bachner, G., Duelli, S., Frei, E., Grossmann, W., Maier, R., Nabernegg, S., Williges, K., Streicher, W., Ochs, F., Magni, M., Tosatto, A., Venturi, E., Passer, A., Kreiner, H., **Scherz, M.**, Truger, B., Vogel, J., & Offenthaler, I. (2021). The Economic Effects of Achieving the 2030 EU Climate Targets in the Context of the Corona Crisis - An Austrian Perspective: Wegener Center Scientific Report 91-2021. Wegener Center Verlag.

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Wieser, A. A., **Scherz, M.**, Passer, A., & Kreiner, H. (2021). Challenges of a Healthy Built Environment: Air Pollution in Construction Industry. Sustainability , 13(18), [10469]. https://doi.org/10.3390/su131810469

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Trummer, P., **Scherz, M.**, Ammerer, G., & Feiel, S. (2021). Nachhaltiger Umgang mit mineralischen Rohstoffen von der Gewinnung bis inklusive Halbzeugherstellung. in Allianz Nachhaltige Universitäten in Österreich (2021): UniNEtZ-Optionenbericht: Österreichs Handlungsoptionen zur Umsetzung der UN-Agenda 2030 für eine lebenswerte Zukunft. UniNEtZ – Universitäten und Nachhaltige Entwicklungsziele

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