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Sustainable procurement for carbon neutrality of buildings: A Life Cycle Assessment (LCA)-based bonus/malus system to consider external cost in the bid price

Marco Scherz, Helmuth Kreiner, Alexander Passer *

Working Group Sustainable Construction, Institute of Structural Design, Graz University of Technology, Technikerstraße 4/IV, 8010, Graz, Austria

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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

* Corresponding author.
E-mail address: alexander.passer@tugraz.at (A. Passer).

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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.

$$\text{GHG emissions}_{\text{BONUS/MALUS}}\,[€] = \left(\text{GWP}_{\_n}\,[\text{t CO}_2\text{eq}] - \frac{\sum_1^n \text{GWP}_{\text{BIDDER}}}{n}\right) \text{x RBCF}_{\text{carbon price}}\,[€/\text{tCO}_2\text{ eq}]$$

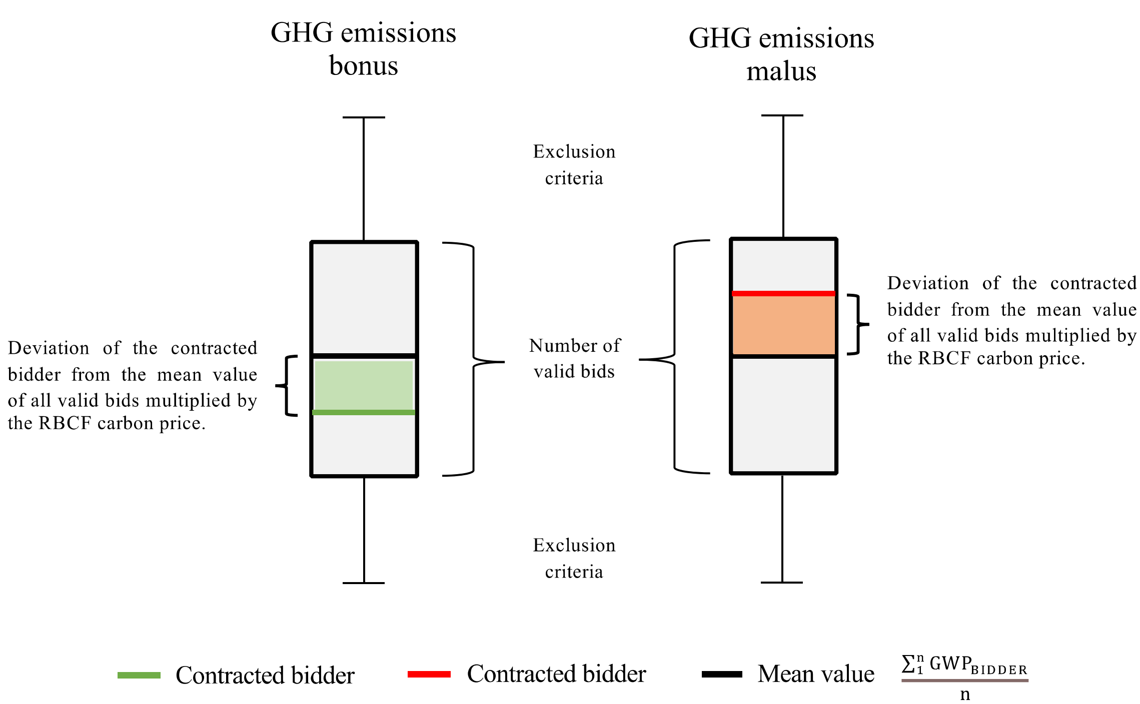

Fig. 1. Calculation principle for calculating the GHG emissions bonus/malus.

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

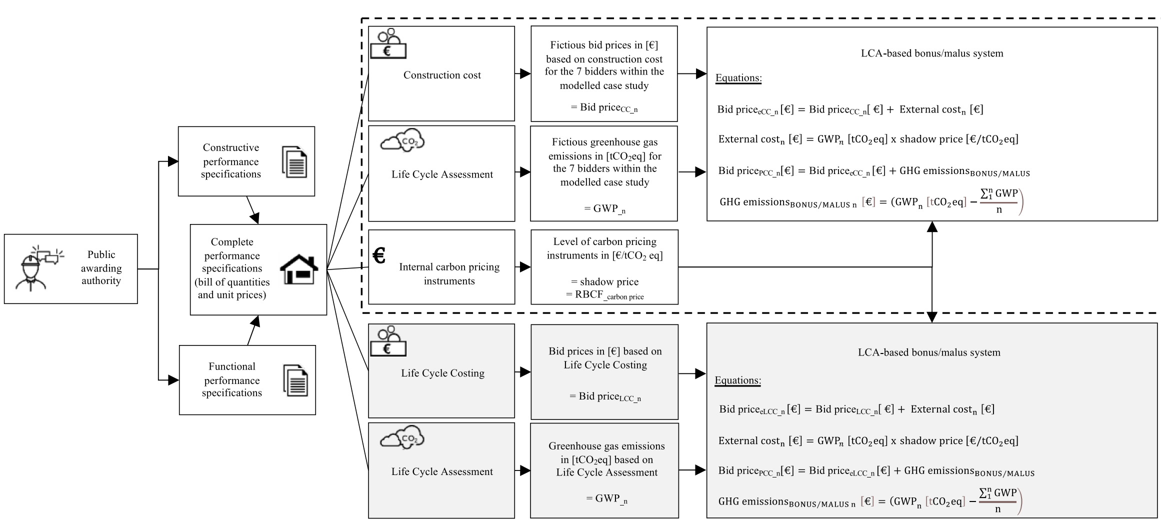

Fig. 2. Theoretical framework of the LCA-based bonus/malus system highlighting the methodological approaches and the equations. The framed box represents the content of this study, which examines bid prices based on construction cost. The application of the LCA-based bonus/malus system by means of bid 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

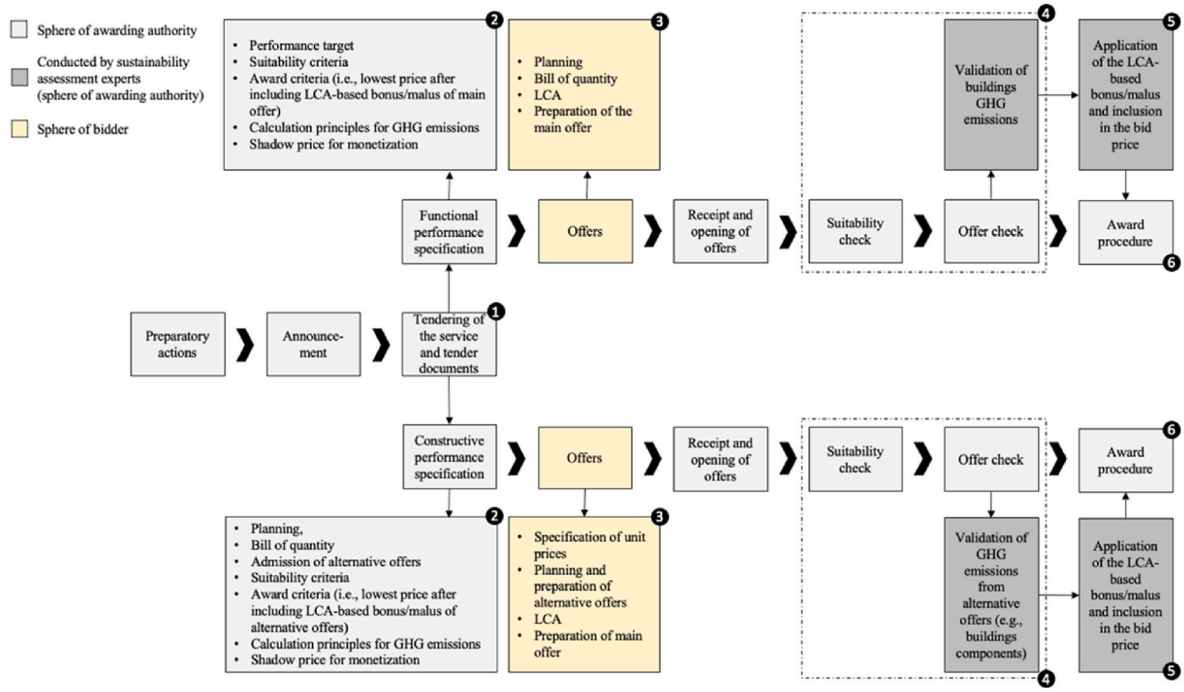

Fig. 3. Spheres of awarding authorities and bidders for the two tender types (i) tender with functional performance specifications and (ii) tender with constructive performance specifications, as well as the detailed tender specifications for the application of the LCA-based bonus/malus system.

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:

$$\text{External cost}_{\_n}\ [€] = GWP_{\_n}\ \left[\text{t } CO_2\text{eq} / m^2_{NFA}\text{ a}\right] \text{ x shadow price } [€ / tCO_2\text{eq}]$$

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	NFA	RSP	GWP	Carbon price scenario 1	Carbon price scenario 2	External cost scenario 1	External cost scenario 2
	[€]	[kg CO_2eq/m^2 $_{NFA}$ a]	[m^2]	[a]	[t CO_2eq]	[€/tCO_2eq]	[€/tCO_2eq]	€	€
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 m^2, RSP 50 years.

	Bid price	GWP	GWP	External cost	Bid $price_{eCC}$	Share external cost/bid price
	[€]	[kgCO_2eq/m^2_{NFA} a]	[tCO_2-eq]	[€]	[€]	[%]
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 m^2, RSP 50 years.

	Bid price	GWP	GWP	External cost	Bid $price_{eCC}$	Share external cost_/bid price
	[€]	[kgCO_2eq/m^2_{NFA} a]	[tCO_2eq]	[€]	[€]	[%]
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:

$$\text{GHG emissions}_{BONUS/MALUS} [€] = \left(GWP_{\_n}\ [t\ CO_2eq] - \frac{\sum_{1}^{n} GWP_{BIDDER}}{n} \right) \text{x}\ RBCF_{\text{carbon price}}\ [€ / tCO_2eq]$$

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 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_2eq]	[tCO_2eq/]	[€]	[€]	[%]
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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