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Environmental life cycle costing at the early stage for supporting cost optimization of precast concrete panel for energy renovation of existing buildings

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ABSTRACT

Around 35% of the buildings in Europe are over 50 years old and almost 75% of the building stock is energy-inefficient. A European project VEEP is developing an innovative prefabricated concrete element (PCE) system to improve the thermal performance of new buildings (PCE1) and old buildings (PCE2). This study focused on retrofitting of old buildings via over-cladding of the building envelope with PCE2. This study aims to from a building owner/consumer's perspective to explore the life cycle economic performance of the PCE2 system at an early stage and associated cost optimization strategies under the European context. This study tries to answer four questions: 1) whether the use of the PCE2 leads to an economic advantage over a specific life cycle of an existing building. 2) what is the biggest cost stressor in the life cycle of a PCE2? 3) the potential route for further cost optimization. and 4) how would the discount rate affect the life cycle costs, especially when Europe has entered a negative rate age? A typical apartment building in the Netherlands is selected as the case study for dynamic thermal simulation, in which the heating and cooling energy demands before and after refurbishment with PCE2 will be evaluated. By employing environmental life cycle costing (LCC), the life cycle costs over 40 years and associated strategy for cost optimization were investigated. This research not only unveils meaningful financial implications on resource-efficient building energy renovation in Europe but also provides insight on methodological dilemmas within the application of LCC.

1. Introduction

The building sector is responsible for 36% of CO_2 emissions and 40% of energy consumption in the European Union (EU), and almost three-quarters of the buildings in Europe are energy-inefficient [1]. Directives at EU level have been enacted for cost-effective renovation of buildings. In 2010 the EC enacted the revision of the Energy Performance of Buildings Directive (EPBD, 2010/31/EU) aiming to optimize the energy efficiency of the EU buildings by the cost-effectiveness of energy efficiency measures [2]. The Energy Efficiency Directive (EED, 2012/27/EU) states in Article 4 that Member States (MS) shall establish a long-term strategy for mobilizing investment in the renovation of the building stock [3].

As a MS of the EU, the Netherlands was requested to draw up national energy efficiency plans. For instance, The EED states in Article 24 that MSs shall submit National Energy Efficiency Action Plans (NEEAP) which cover energy efficiency optimization measures and expected and/or achieved energy savings by 2014, and every three years thereafter [3]. The fourth NEEAP for the Netherlands was drafted by the Minister of Economic Affairs and the Minister of the Interior and Kingdom Relations in the Netherlands as part of the obligation to report to the NEEAP [4]. For the period from 2021 to 2030, each EU MS was also required to draft a National Energy and Climate Plan (NECP) indicating methods to achieve a series of targets by 2030 [5]. The Dutch building energy renovation strategy is mainly based on the Energy Agreement for

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Abbreviations

ADR	Advanced dry recovery technology
BAU	Business-as-usual
CDW	Construction and demolition waste
CRLWCA	Coarse recycled lightweight concrete aggregate
DGR	Dry grinding & refining system
EC	European Commission
EED	Energy Efficiency Directive
EoL	End-of-life
EPBD	Energy Performance of Buildings Directive
EPS	Expandable polystyrene
EU	European Union
FRLWCA	Fine recycled lightweight concrete aggregate
HAS	Heating-air classification system
LCA	Life cycle assessment
LCC	Life cycle costing
LCSA	life cycle sustainability assessment
MS	Member State of the EU
NECP	National Energy and Climate Plan
NEEAP	National Energy Efficiency Action Plans
PCE	Prefabricated concrete element
PCE1	Prefabricated concrete element for new buildings
PCE2	Prefabricated concrete element for existing buildings
RFUA	Recycled fiber wool ultrafine admixture
RGUA	Recycled glass ultrafine admixture
SETAC	Society of Environmental Toxicology and Chemistry
URLWCA	Ultrafine recycled lightweight concrete aggregate
VEEP	European Union Horizon 2020 project VEEP

Sustainable Growth [6], which includes plans on energy conservation in the built environment. According to the Netherlands Environmental Assessment Agency, to respond to energy efficiency ambitions in those plans, the Netherlands committed to an energy-neutrality target within the Dutch built environment by 2050. This means of 7.5 million dwellings, 80% are to be renovated to energy-neutral levels by 2050, which indicates 170,000 homes are to be renovated per annum [7].

Moreover, gradual aging of building stock triggers massive deconstruction, bringing about the skyrocketing of construction and demolition waste (CDW). To support the energy renovation and CDW management, a European project VEEP has been developing an innovative technological system to recycle CDWs for fabricating multilayer prefabricated concrete elements (PCE) that are employed to optimize the energy performance of buildings. The technological system includes an integrated *Advanced drying recovery technology* (ADR) and *Heating-air classification system* (HAS) for fully recycling end-of-life (EoL) normal-weight and lightweight concrete for production of secondary coarse and fine concrete aggregate and cementitious particle [8–10]. Additionally, the insulating fiber wool waste and glass waste are recovered via *a Dry grinding & refining system* (DGR), to produce secondary ultrafine aggregate [11]. Those recycled materials are applied to the production of new normal-weight and lightweight concrete, and green aerogel in the final product PCE. The PCE solutions will be conceived both for new building envelope/recladding (PCE1) and for building envelope refurbishment/over-cladding (PCE2). PCE1 and PCE2 are suitable for most building families such as collective residential buildings, office buildings and school buildings. The life cycle performance of PCE1 was already presented in the previous study [11], and this study only focuses on the PCE2.

The PCE2 system is at its designing stage, so it is unclear whether the implementation of this PCE2 system will necessarily provide an improvement in overall economic benefits along the life span of a building. The goal of this study is at an early stage from the consumer's perspective to compare the economic viability and associated optimizing strategies of a wall of building refurbished with the VEEP PCE2 to the wall of building refurbished with the business-as-usual (BAU) PCE2, and to the wall of building without refurbishment under the context of an EU MS the Netherlands. Thus, this study aims to answer the following research questions, from an empirical aspect: 1) whether the use of PCE leads to an economic advantage over a specific life cycle of an existing building; 2) what is the biggest cost stressor in the life cycle of a PCE2? 3) the potential route for further cost optimization; and 4) how would the discount rate affect the life cycle costs, especially when some European countries have entered a negative rate era? A virtual apartment in Europe is selected for dynamic thermal simulation, in which the heating and cooling energy demands before and after refurbishment with PCE2s will be evaluated. By employing environmental life cycle costing (LCC), the life cycle economic performance of the apartment refurbished with or without PCE2 over 40 years was investigated, and associated strategies for cost optimizations were introduced. In addition, the potential costs for the implementation of the VEEP PCE2 system in the Netherlands for different cohorts of the buildings, as well as in other EU MSs, were compared.

This research not only provided financial implications on building energy renovation but also identified the debates in LCC that need to be further explored to facilitate the integration of the LCC with life cycle assessment (LCA) and life cycle sustainability assessment (LCSA).

2. Methods and materials

2.1. Environmental life cycle costing

LCC was initially developed as a cost management tool for purely financial purposes [12]. Conventional LCC mainly concerns acquisition and ownership costs. With the growing concerns about sustainability and its three pillars [13], LCC was not only formulated as the economic dimension of LCSA via a conceptual equation [14,15]: LCSA = LCA + environmental LCC + social LCA, but also was adopted in an environmental and social context, such as the variants of LCC: full environmental LCC and societal LCC [16].

Environmental LCC was initially defined by Rebitzer et al. [17] as an LCA-based LCC method, which utilizes an LCA model as a basis to estimate incurred costs in a product assessment. The Society of Environmental Toxicology and Chemistry (SETAC) Europe working group on LCC formally categorized LCC into: (i) conventional LCC which only includes internal costs; (ii) environmental LCC which includes internal costs and external costs expected to be internalized; and (iii) societal LCC which contains internal, plus all external, costs [18]. Additionally, Hoogmartens et al. [16] explain an uncommonly accepted concept, namely full environmental LCC, which extends environmental LCC with monetized, non-internalized environmental costs as societal LCC does.

This study employed environmental LCC as an appraisal tool to explore the economic performance and strategies for cost optimization of the VEEP PCE2. The term "environmental" indicates the structure of the LCC is established in a manner that is harmonized with that of a standard LCA conforming to ISO 14040 [19]. Whether an LCC referring to a planning or past product system leads to prospective LCC or retrospective LCC. Due to lack of historical data information, a prospective LCC may encounter a wider range of uncertainty. A prospective approach was employed to look into the PCE2 system at its designing stage to support future decision-making.

The environmental LCC was deployed based on a four-step framework from an overarching eco-efficiency assessment [8]: (i) goal and scope definition; (ii) life cycle economic inventory analysis; (iii) life cycle economic impact assessment; (iv) interpretation. The life cycle stages of the LCC analysis were defined according to the building assessment framework from CEN EN 15804 [20]. If not specified, the term "LCC" mentioned hereafter represents environmental LCC.

2.2. Goal and scope definition

2.2.1. Goal and scope

The goal of this study is to compare the financial profitability and optimization potentials of manufacturing, and using the BAU PCE2 and VEEP PCE2 as an over-cladding façade of the existing building compared to the original wall of building without any refurbishment. Both BAU and VEEP PCE2 are expected to be preferentially implemented to those obsolete buildings constructed before 1960. The environmental LCC only accounts for internal costs, which usually consists of production budgets and transfers (such as taxes, subsidies and fees). LCA was not performed, thus external costs are not considered.

All productive activities are assumed to occur in the Netherlands. All cost data were collected based on the current market information in the Netherlands. The life cycle phases are classified according to the life cycle stages and modules for the building assessment framework defined in EN 15804 [20] as shown in Table 1. Based on the building life cycle information, four stages are included in the LCC analysis: (i) production stage; (ii) use stage; (iii) installation stage; (iv) EoL stage. The LCC investigates an entire life cycle from a single perspective of a consumer of PCE2. However, cost analysis was broken into two separate segments: costs incurred by the manufacturer and by the consumer.

The production stage includes two procedures, which are raw material production, and PCE2 manufacturing. In the process of raw material production, raw materials will be prepared for the fabrication of the PCE2, including raw materials for lightweight concrete (expanded clay, sand, plasticizer, etc.), steel frame, and insulation layer. Both primary and secondary raw materials will be incorporated into the production of green lightweight concrete and green aerogel for further manufacturing of the VEEP PCE2. In the process of PCEs manufacturing, a panel will be fabricated with the mentioned raw materials. At the use stage, the PCE2 will be transported to the construction site for installation. Then dynamic thermal simulations is performed to compare the heating and cooling energy demands of a virtual apartment block with or without refurbishment of the PCE2 in the capital of the Netherlands, Amsterdam. At the EoL stage, the PCE2 will be dismantled and disposed.

Table 1
Scope of the LCC analysis according to life cycle stages and modules for the building assessment information system defined in EN 15804:2012. Note: modules marked with "/" denote the economic effect of this module was not considered in the analysis.

Building life cycle information	EN 15804:2012 Information modules code	PCE2 system under the EN 15804:2012 Information modules
Production Stage (A1-A3, D)	A1: Raw material supply A2: Transport A3: Manufacturing D: Reuse, recovery, recycling	A1: Production of virgin raw materials for lightweight concrete and aerogel A2: Transport of virgin raw materials; Transport of recycling facilities; transport of secondary raw material A3: Manufacturing of PCE2 (including material manufacturing of concrete and insulation) D: Recycling of ferrous materials; processing of lightweight concrete, fiber wool waste, and glass waste for producing secondary raw material
Construction process stage (A4-5)	A4: Transport A5: Construction installation process	A4:/ A5: Transport and installation of PCE2
Use stage (B1-7)	B1: Use B2: Maintenance B3: Repair B4: Replacement B5: Refurbishment B6: Operational energy use B7: Operational water use	B1:/ B2:/ B3:/ B4:/ B5:/ B6: Operational energy use B7:/
End-of-life stage (C1-4)	C1: De-construction demolition C2: Transport C3: Waste process C4: Disposal	C1: Dismantling of PCE2 C2: Transport of recycling facilities; transport of waste C3: Concrete processing C4: Landfill of insulation materials

2.2.2. Scenario development

Based on the defined scope, three scenarios were developed in this study: (i) BAU TW, (ii) BAU PCE2, and (iii) VEEP PCE2. The BAU TW scenario denotes the building uses the traditional wall as façade without refurbishment. The reference building is assumed to be constructed between 1941 and 1960. Based on the statistic from the Buildings Performance Institute Europe [21], the thermal transmittance (U-value) of the external walls for the target building group in the Netherlands is assumed 2.70 W/(m^2.K) for the thermal simulation in this study. Regarding the economic assessment of the BAU TW scenario, cost occurs only at the use stage.

The BAU PCE2 scenario represents the building with a traditional wall in BAU TW to be refurbished with BAU PCE2. The BAU PCE2 scenario is taken as the reference with the same structure as that of the VEEP PCE2. The cross-sectional views of the BAU PCE2 and VEEP PCE2 for over-cladding building envelopes are presented in Fig. 1. The normal lightweight concrete, which does not contain any recycled materials, is used for the BAU PCE2 as the exterior layer. A regular insulating material expandable polystyrene (EPS) is selected as the insulation layer. The thermal transmittance (U-value) of the traditional wall refurbished with BAU PCE2 is 0.367 W/(m^2K). With respect to life cycle costs of the BAU PCE2 scenario, costs are incurred in four life cycle stages.

The VEEP PCE2 scenario describes the building with the traditional wall in BAU TW to be retrofitted with the VEEP PCE2. Compared to the BAU PCE2, the VEEP PCE2 has higher resource efficiency due to incorporated secondary raw materials. The VEEP PCE2 uses green aerogel with high thermal performance as the insulation layer. The thermal conductivity of the aerogel for the PCE2 is set as 0.0157 W/(m.K). The green lightweight concrete also contains secondary raw materials such as secondary coarse and fine aggregate, and secondary contentious particle, amounting to more than 57% of lightweight concrete by weight. The U-value of the traditional wall refurbished with VEEP PCE2 is 0.203 W/(m^2K). Regarding the life cycle costs of the VEEP PCE2, costs are incurred in four life cycle stages. Further introduction of the VEEP PCE2 system can be found in the supplementary document.

2.2.3. Functional unit

In the BAU PCE2 and PCE PCE2 scenario, it is assumed that the required building façade per 1 m^2 of flooring area amounts to 0.55 m^2 of PCE2. The functional unit is set as: maintaining the thermal comfortableness of 1 m^2 flooring area of a building (with or without the implementation of the PCE2 system for refurbishment) and active heating and cooling for 40 years based on the climatic condition of Amsterdam.

2.3. Life cycle economic inventory analysis

The assessment boundaries for the three scenarios are depicted in Fig. 2. Based on the system boundaries, details of the life cycle inventory of these scenarios are discussed according to the four life cycle stages.

In a national accounting system, internal costs can be measured either in market prices: adding all expenditure on products, or by adding all factor costs [18]; the latter are market prices excluding transfers. However, for an LCC study, market prices and factor costs are used in a mixed manner. It is difficult and incorrect to use market prices and

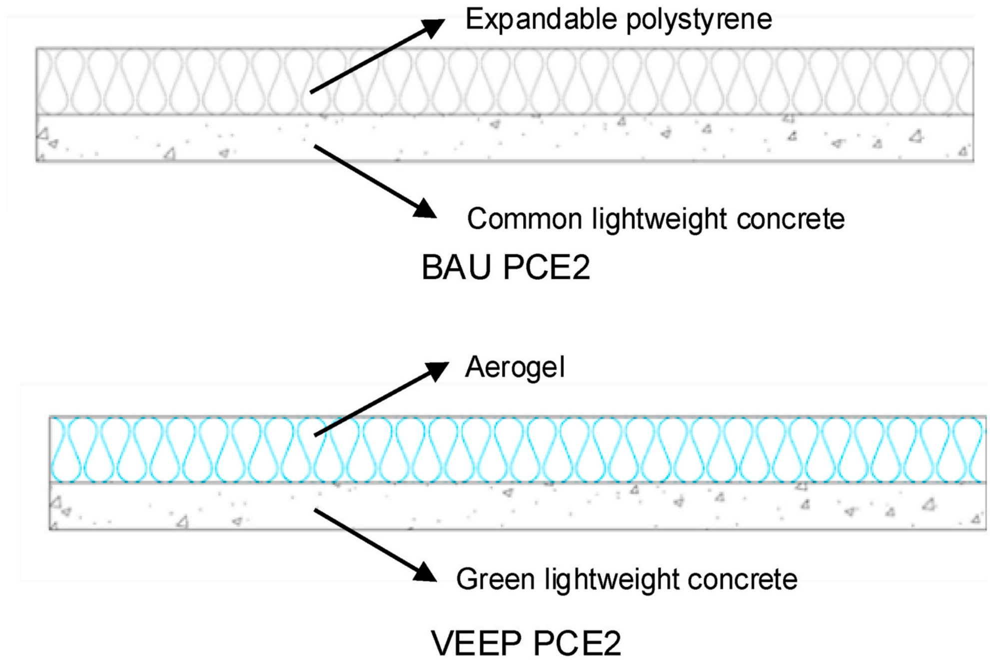


Fig. 1. Cross-sectional views of BAU PCE2 (above) and VEEP PCE2 (below). Note: BAU PCE2 and VEEP PCE2 share the same dimension: length 2000 mm, width 2000 mm, thickness 130 mm.

factor costs alone, and the reason will be elaborated later in 4.2. The cost information was collected via Ecoinvent cost database 3.4 for OpenLCA 1.9, surveys by email and telephone and literature.

2.3.1. *Production stage*

In the VEEP PCE2 scenario, EoL lightweight concrete is recycled by the integrated ADR and HAS technology for the production of ultrafine recycled lightweight concrete aggregate (URLWCA), fine recycled lightweight concrete aggregate (FRLWCA) and coarse recycled lightweight concrete aggregate (CRLWCA), as illustrated in Fig. 3. The DGR can process glass/insulating fiber wool waste into recycled glass ultrafine admixture (RGUA) and recycled fiber wool ultrafine admixture (RFUA) as depicted in Fig. 3. The mass balance for ADR and HAS processing normal-weight siliceous concrete and for DGR was discussed in the previous study [8,11], based on which integrated unit costs (including waste transport raw material production, utilities, personnel, equipment) of URLWCA, FRLWCA, CRLWCA, RGUA, RFUA were determined. As can be seen from Fig. 3 that mass balance varies between processing lightweight and normal-weight concrete. However, the integrated unit costs of the coarse, fine, ultrafine fraction from processing lightweight concrete are identical to those materials made from normal-weight concrete due to the mass-based allocation scheme. The cost information for the production stage is presented in the supplementary document.

2.3.2. *Installation stage*

After a fabrication process at a factory, PCE2 will be transported to a construction site for installation. The installation is a labor-intense activity; around 90% of the expenditure is from personnel costs. The cost information for the installation stage is presented in the supplementary document.

2.3.3. *Use stage*

At the use stage, the operation time is set as 40 years, during which additional repair and maintenance for the traditional wall and PCE2 were not considered. The dynamic thermal simulation was conducted on a virtual typical apartment in the climatic condition of Amsterdam through the software EnergyPlus and DesignBuilder, to compare the thermal characteristics of three scenarios. Heating demand can be directly linked to the natural gas consumption for heat generation from a boiler. With respect to cooling, cooling energy need is modified into the electricity demand of the air conditioning based on an energy efficiency ratio. The seasonal energy efficiency ratio for household air conditionings in DIN V 18599 is set as 4.7 [22]. The annual demand for heating and cooling of three scenarios are shown in Table 2. Other details of the dynamic thermal stimulation are elaborated in the supplementary document.

2.3.4. *End-of-life stage*

At the EoL stage, the building is to be demolished. Dismantling of PCE2 is considered a process within the destruction of the building, thus its economic impact was not considered. However, the treatments of additional waste such as EoL concrete, insulation material and steel frame generated from PCE2 was taken into account. The EoL concrete is to be crushed in situ by a crusher. Costs incurred by crusher transport are split based on the total amount of EoL concrete generated at the demolition site, thus it is negligible. The steel beams and welded nets are sold directly on-site. The insulation materials are transported to the landfill site. The cost information for the EoL stage is presented in the supplementary document.

2.4. *Life cycle economic impact assessment*

In the phase of economic impact assessment, questions on how the cost will be categorized and structured, and how will costs incurred in different life cycle stages be aggregated, are discussed.

Regarding cost categorization, there are commonly three ways: expenditure-based, actor-based and life cycle-based [8]. Since integrated unit costs were used, cost information is not specific and detailed enough to be broken down from an expenditure aspect. The perspective of the consumer was used, and two cost bearers exist in the LCC, namely manufacturer and consumer. There is only one main actor in each life cycle stage, thus, actor-based and life cycle-based will be identical. Therefore, a life cycle-based cost breakdown structure was applied. Costs incurred along the life cycle is categorized into production costs, operation costs and EoL cost.

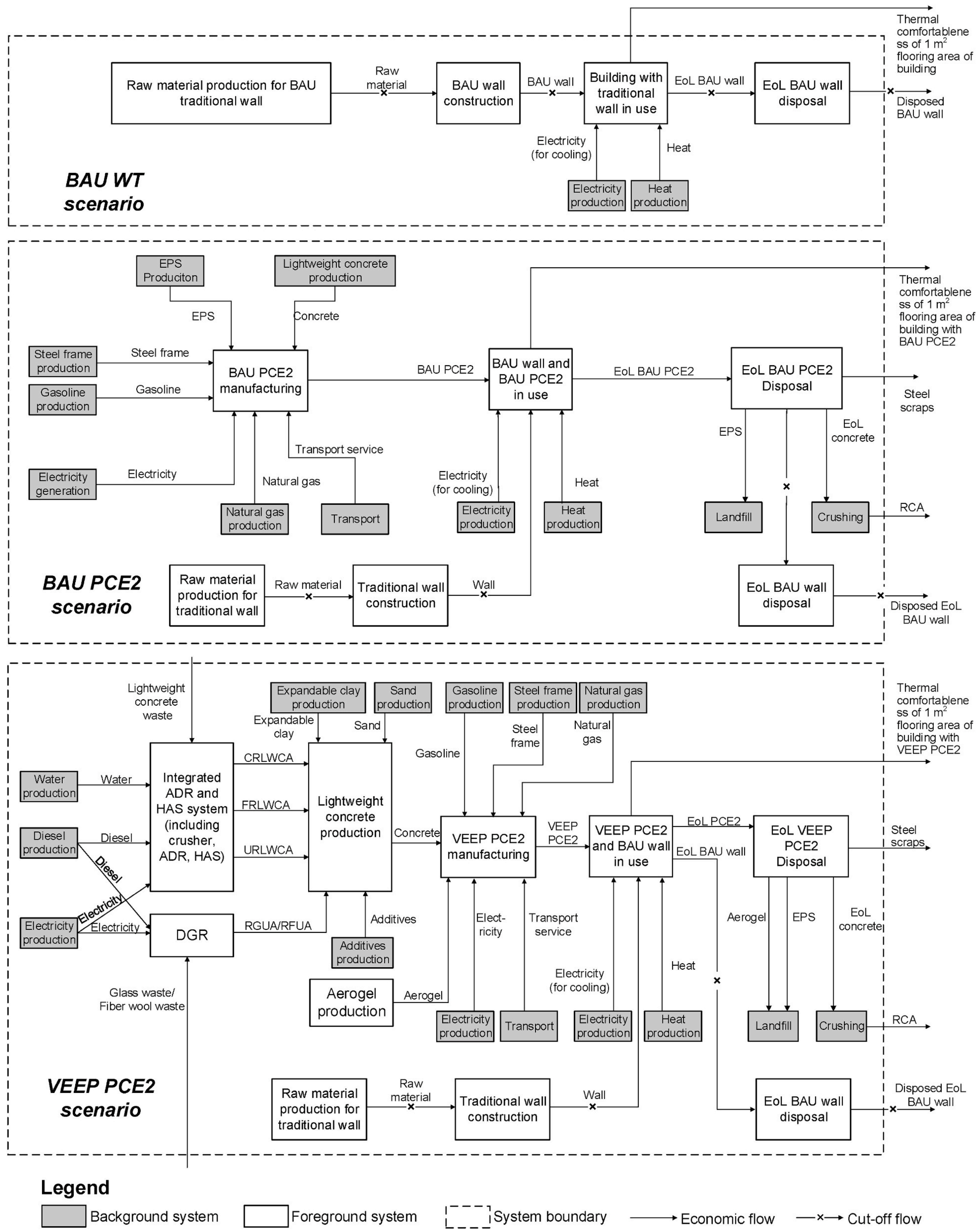


Fig. 2. System boundaries for the BAU TW scenario (above), the BAU PCE2 scenario (middle), and the VEEP PCE2 scenario (below). Note: ADR represents Advanced Dry Recovery system; BAU denotes business-as-usual; CRLWCA represents coarse recycled lightweight concrete aggregate; DGR indicates Dry Grinding & Refining system; EoL represents end-of-life; EPS: expandable polystyrene; FRLWCA denotes Fine lightweight recycled concrete aggregate; HAS represents Heating-Air Classification System; PCE2 represents prefabricated concrete element for building retrofit; RGUA represents recycled glass ultrafine aggregate; URLWCA represents Ultrafine recycled lightweight concrete aggregate; VEEP represents European Union Horizon 2020 project VEEP.

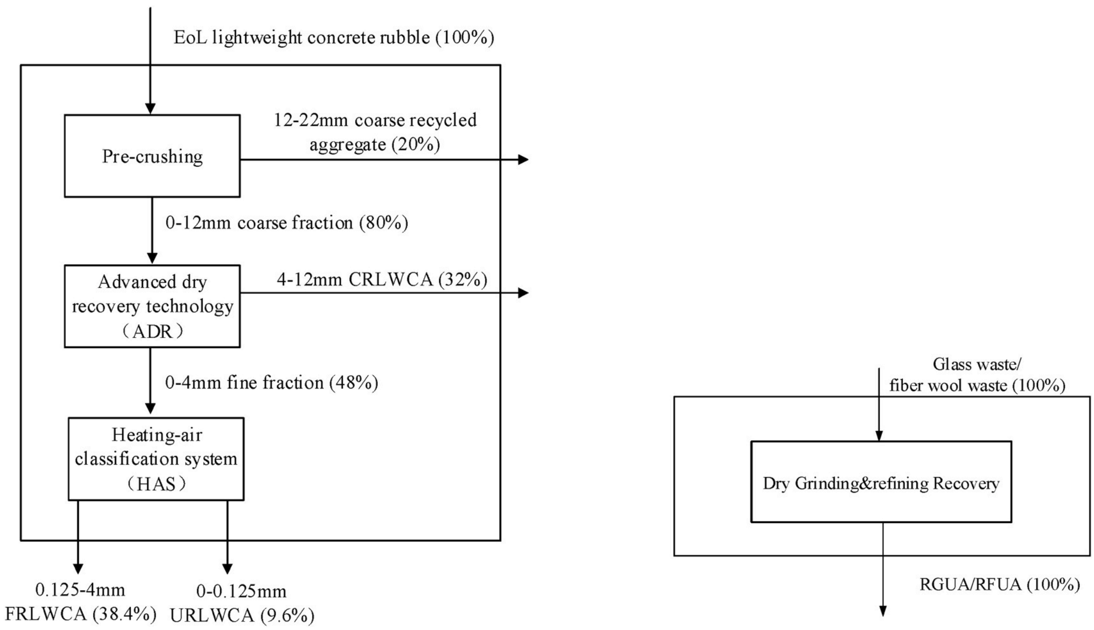


Fig. 3. Mass balance of integrated EoL lightweight concrete recycling (left) and glass waste recovering (right) system. Note: URLWCA represents ultrafine recycled lightweight concrete aggregate; RGUA denotes recycled glass ultrafine admixture; RFUA indicates recycled fiber wool ultrafine admixture; FRLWCA represents fine recycled lightweight concrete aggregate; CRLWCA represents coarse recycled lightweight concrete aggregate; ADR represents advanced dry recovery technology; HAS represents heating-air classification system.

Table 2
Heating and cooling demand of three scenarios.

	BAU TW kWh/ (m^2·year)	BAU PCE2 kWh/ (m^2·year)	VEEP PCE2 kWh/ (m^2·year)
Annual heating demand	99.80	51.40	46.68
Annual cooling demand	1.31	2.03	2.29
Modified electricity consumption for annual cooling demand	0.28	0.43	0.49

With respect to the effect of the time on costs, the discount rate is applied to modify costs incurred at different life cycle stages. The historical time-series interest rate for the Netherlands and the Euro area is visualized in Fig. 4. The interest rate for the Netherlands as well as the Euro area presents a descending trend and ends at around 0% in 2020. Thus the discount rate for the study was set 0%, literately a static-state costing system.

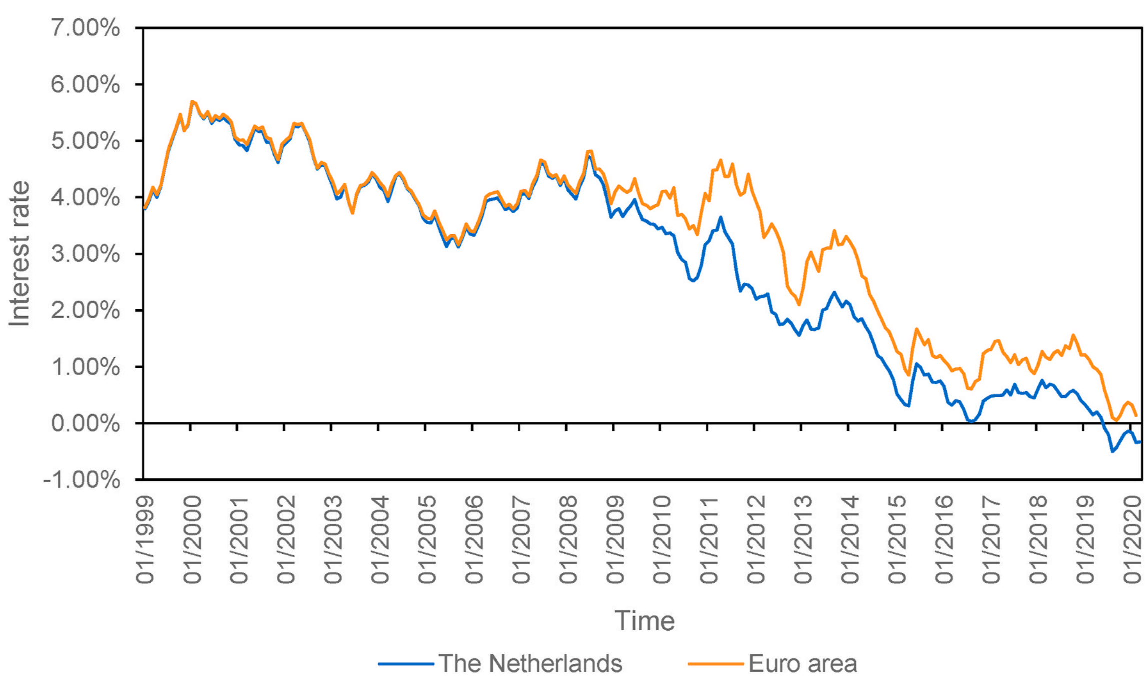


Fig. 4. Time-series interest rate for the Netherlands and Euro area, data from De Nederlandsche Bank [23].

3. Results and interpretation

3.1. Life cycle costs of three scenarios

The results of the LCC from a consumer perspective are shown in Fig. 5. The life cycle costs of the VEEP PCE2 is 13% lower than that of the BAU PCE2, however 22% higher than that of the BAU TW Scenario. The operation costs account for around 70% of the life cycle costs of the BAU PCE2 and VEEP PCE2 scenario, while the EoL costs are almost negligible. Due to the utilization of secondary raw materials, the production costs of the VEEP PCE2 are 30% lower than that of BAU PCE2. Regarding the VEEP PVE2, the three biggest cost stressors are heating costs (38% of the life cycle costs), installation costs (35%), and aerogel costs (20%), amounting to 93% of the life cycle costs.

3.2. Strategies on cost optimizations

Considering those three main cost elements, relevant cost-optimization strategies are: extension on the life span of PCE2, full and partial reuse of PCE2 and cost-effective installation.

3.2.1. Service lifetime of PCE2

The heating demand of the BAU PCE2 and VEEP PCE2 scenario is directly determined by their thermal performance. Adjusting the structure of PCE2, for instance by increasing the thickness of the aerogel layer, can lower the U-value of PCE2, however this increases the production costs as well. Reducing the heating demand by modifying the structure of a PCE2 is a complicated systematic engineering process. It is assumed the dimensions of the aerogel layer of the PCE2 already reached an optimum condition and alteration on the thickness of the insulation layer is omitted from this study.

The lifetime of a PCE2 can also minimize its life cycle costs. At the lab scale, the life span of the VEEP PCE2 is assumed 40 years. The average lifetime of residential buildings in the Netherlands is around 120 years [24]. The building in this study is considered to be constructed before 1960 and its rest lifetime may be more than 40 years. It is assumed the service lifetime of PCE2 can be extended to a maximum of 60 years without additional repair or maintenance. The modified life cycle costs of BAU PCE2 and VEEP PCE2 are presented in Fig. 6 (a). When the life cycle of PCE2 is prolonged to 60 years, the life cycle costs of VEEP PCE2 could be slightly lower than that of BAU TW.

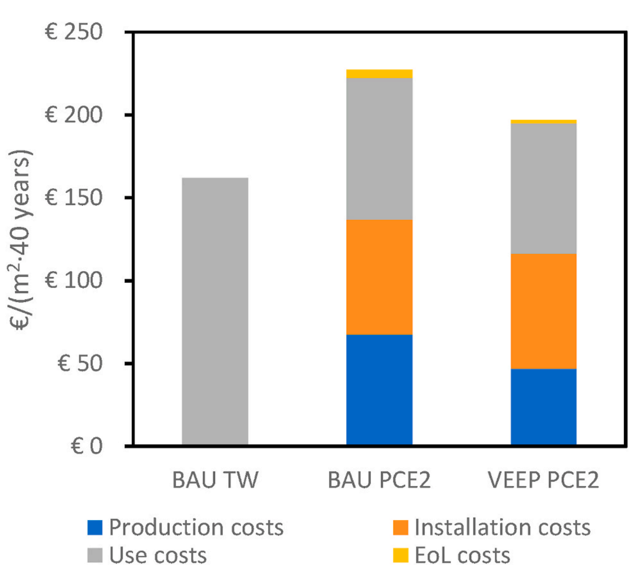


Fig. 5. Life cycle costs of the BAU TW, BAU PCE2, VEEP PCE2 scenario.

3.2.2. Installation of PCE2 with novel anchoring systems

If a connection/joint between PCEs is considered permanent, such as welded connections, adhesive anchors or grouting or dry packing of connections, then PCEs cannot be separated and disassembled into individual elements without any damages. If the installation systems for PCE2 consist of the HALFEN system, which allows a quick, flexible and simple installation, PCE2 can also be easily disassembled and detached from the old structure/wall at its EoL stage for reuse. Over 90% of the installation costs result from personnel costs. As the dismountable anchoring solution is expected to a large degree reduce the labor-hours during the installation of PCEs, it is assumed 10%, 30% and 50% of the installation costs can be reduced in BAU PCE2 and VEEP PCE2 scenarios. The modified life cycle costs of each scenario are presented in Fig. 6 (b).

3.2.3. Reusability of PCE2

According to the waste hierarchy of the EU [25], the reuse of waste has a higher priority than recovery. One prominent feature of the precast concrete element is its reusability, especially the non-structural element. Besides, the development of the novel anchoring system in the concrete element further boosts the potential of reuse.

The partial reusability on the concrete and insulation layer, and the full reusability on an entire PCE2 are considered. Considering the composition of CDW, more than 90% of the value embedded in CDW results from metallic waste [26]. However, the amount of steel beams and welded nets used in PCE2 is negligible, compared to concrete and insulation. Thus, the recyclability of steel frames is omitted.

The reuse of an EoL item in the LCC analysis was modeled as avoiding additional production of this item at the production stage and avoiding disposal of this item at the EoL stage. Full reuse of PCE2 represents PCE2s being integrally separated from the building and reused for refurbishing other buildings. Partial reuse means the insulation layer and concrete layer are reused for substituting new insulation and concrete in the manufacturing of PCE2.

10% of physical loss is assumed in the process of reuse, and the loss fraction is compensated by new production. Additional costs incurred during the process of reuse are included in the physical loss. The life cycle costs of PCE scenarios with or without reuse are presented in Fig. 5 (c). It can be seen that the reuse of insulation materials has a considerably positive effect on cost reduction, while the reuse of the concrete layer barely affects the life cycle costs. For the VEEP PCE2, its life cycle costs can be decreased to €163 if the aerogel layer of the PCE2 is successfully reused.

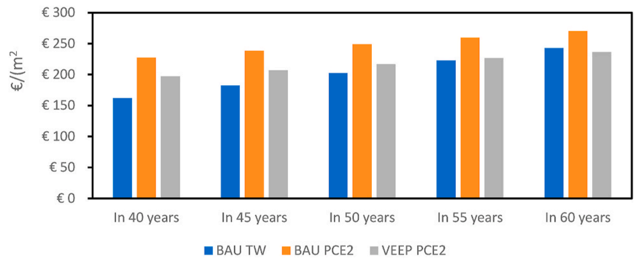
3.2.4. Aggregation of cost optimizations

To gain a better understanding of the holistic cost optimization of the PCE2 system, the proposed three strategies were aggregated to reflect on the extent of cost optimization. Three levels of optimization are defined: low-level, medium-level and high-level, as shown in Table 3.

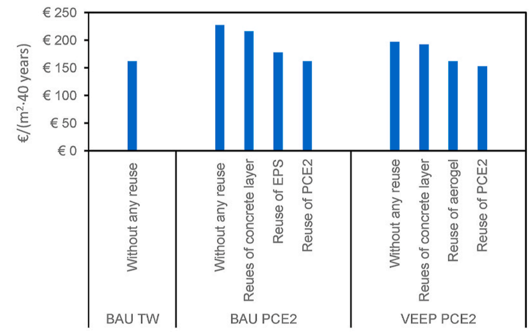
Due to different time spans in each level, the reductions in life cycle costs cannot be directly compared. Therefore, the result of LCC is expressed in the form of annual value. As it is depicted in Fig. 6 (d) after medium-level optimization the annual costs of BAU PCE2 and VEEP PCE 2 is lower than that of the BAU TW scenario. After high-level optimization, the annual costs of the VEEP PCE2 is 1.42 €/annual lower than that of the BAU TW scenario, amounting to around 85 €/m^2 in 60 years.

3.3. Effect of discount rate

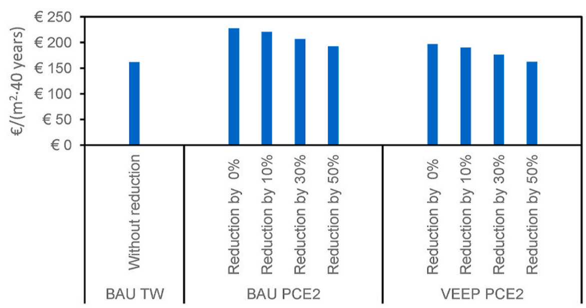
To what extent the fluctuation of the discount rate would affect the life cycle costs is explored. Applying a discount rate to an LCC analysis depends on specific research questions to be answered. For example, the discount rate ranges from 2% in long-term public projects, and 5–15% in private investments, to 20% in the high-tech area [18]. Since in this study the operation cost is borne by individual consumers, the discount rate is related to the interest rate in Fig. 4. A range of (-1%,3%) is assumed to model the fluctuation of the life cycle costs responding to



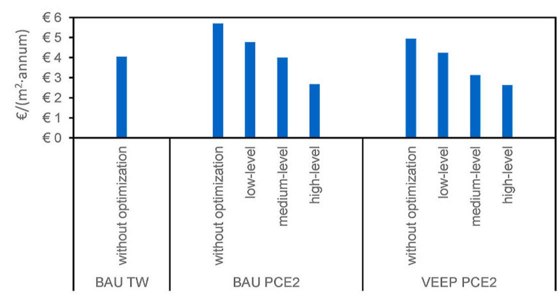
(a) Comparison of life cycle costs of three scenarios in different lifetimes



(c) Comparison of scenarios with or without reuse of wastes



(b) Modified life cycle costs by reduction of installation costs by 10%, 30%, 50% of three scenarios



(d) Annual cost of three scenarios in low-, medium-, high-level optimization

Fig. 6. Results of the cost optimization strategies.

Table 3
Magnitude of cost optimization.

	Low-level optimization	Medium-level optimization	High-level optimization
Description	Service lifetime: 47 years Installation costs reduction: 10% Reusability: reuse of concrete layer	Service lifetime: 54 years Installation costs reduction: 30% Reusability: reuse of aerogel layer	Service lifetime: 60 years Installation costs reduction: 50% Reusability: reuse of entire PCE2

discount rates. The BAU TW, BAU PCE2 with medium-level optimization and VEEP PCE2 with medium-level optimization are selected as examples under a 54-year service lifetime. The annual energy cost and EoL cost are discounted according to Formula (1) and (2).

$$C_p^t = \frac{C_{heating} + C_{cooling}}{(1+r)^t} \tag{1}$$

$$C_p^{EoL} = \frac{C_{EoL}}{(1+r)^{54}} \tag{2}$$

where C_p^t denotes the net present value of the heating and cooling costs incurred at t year; $C_{heating}$ represents annual heating costs; $C_{cooling}$ indicates annual cooling costs; r denotes discount rate; C_p^{EoL} represents the net present value of the EoL costs incurred at the EoL stage; C_{EoL} denotes the EoL costs.

The life cycle costs of three scenarios with different discount rates are shown in Fig. 7. It can be seen from the trend that a negative discount rate will increase life cycle costs over time, while positive discount rates are supposed to lower it. Regarding PCE2 scenarios, there is an obvious trade-off on additional production costs and lower operation costs. The negative discount rate will amplify the impact of operation costs on the life cycle costs, which enhances the economic advantage for VEEP PCE2 which has lower operation costs. For example, when the average discount rate descends from 0% to -1% over a 54-year time span, the reduction of the life cycle cost of VEEP PCE2 (medium-level) increases

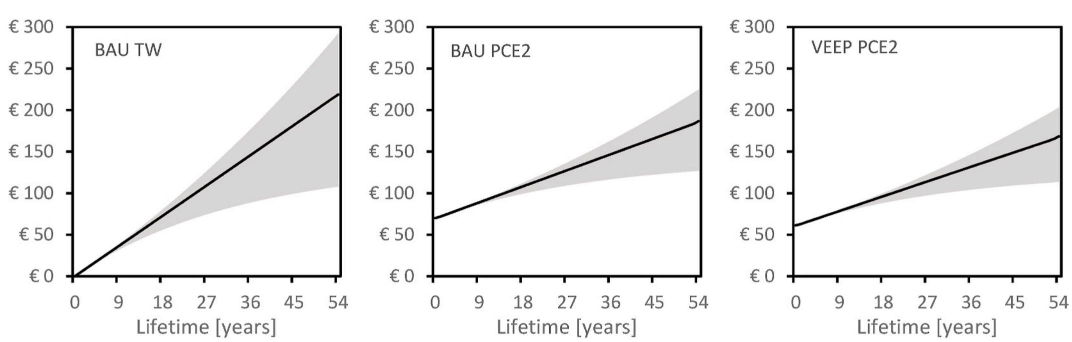


Fig. 7. Life cycle costs of the BAU TW, BAU PCE2 with medium-level optimization, VEEP PCE2 with medium-level optimization under 54-year service lifetime. Note: The minimum limit of life cycle costs was estimated by assuming 3% as the average discount rate; the maximum limit of life cycle costs was estimated by assuming -1% as the average discount rate; the line inside the shaded area represents static-state life cycle costs without discounting. The min/med/max life cycle costs of BAU TW is 107.66 €/218.74/291.93 €; the min/med/max life cycle costs of BAU PCE2 is 126.97/186.77/224.60 €; the min/med/max life cycle costs of BAU PCE2 is 113.59/168.56/203.21 €.

from €50 to €88 compared to BAU TW. As Europe has entered an era of a negative discount rate, using insulation with high thermal performance such as aerogel is likely to be more competitive in the future market of building energy renovation.

On the other hand, it is found that LCC analysis is sensitive to the discount rate. Variation of the discount rate by 1% over a long period, such as 50 years, is expected to noticeably influence the life cycle costs. Compared to the PCE2 scenarios, the BAU TW is more subject to the discount rate because it has higher heating and cooling costs per annum. The life cycle costs of BAU TW would halve if the discount rate increases from 0% to 3%. Furthermore, the discount rate is even able to reverse the results. The life cycle cost of the VEEP PCE2 (medium-level) is €50 lower than that of BAU TW in a static-state costing system, but €6 higher if the average discount rate remains 3% over 54 years.

3.4. Comparison with results to other studies

Many LCC studies, including LCC studies on building facades, have been carried out in the building sector. We used a code (shown in Formula (3)) to systematically search articles in the Web of science Core Collection and found 87 relevant studies. The detailed information on the studies are listed in the supplementary document.

TS=((“life cycle cost” OR LCC OR “life cycle costing”) AND (residential building) AND (wall* OR façade* OR envelope*)) (3)

After reviewing those literature, however, it is difficult to compare the results of this study with other LCC cases due to the diversity of modeling approaches, settings and purposes, and peculiarity in technologies selected and local characteristics. To put the study in context, a comparison analysis has been carried out. The potential costs for the implementation of the VEEP PCE2 system in the Netherlands for different cohorts of the buildings, as well as in other EU Member States are calculated. Because energy costs for cooling are almost negligible in the climatic condition of the Netherlands, the comparison focuses on the energy demand for heating.

Data was collected from the TABULA online database [27] which includes information about building energy renovation in multiple EU MSs. Five apartments in the Netherlands constructed in different periods were selected for comparison. As depicted in Fig. 8, the annual heating costs of building after it has been refurbished with the BAU PCE2 and VEEP PCE2 are between the costs of those five apartments after usual and advanced refurbishment. However, the annual heating costs of two PCE scenarios are significantly lower than the costs of existing state without refurbishment.

From a cross-state comparison of annual heating costs in Fig. 9, the VEEP PCE2 solution can be seen as advanced refurbishment in some middle-latitude states such as Germany or France. However, this may be because the annual heating demand of the basic reference BAU TW is lower than the cases from TABULA. Besides, the latitude of an area can also influence the annual heating demand. The Northern states such as Norway and Denmark have higher annual heating demand, resulting in both PCE2 solutions having remarkably lower heating costs compared to the advanced refurbishment of those two states. However, for low-latitude country like Spain, the heating cost of the VEEP PCE2 is almost equivalent to that of the existing state without any refurbishment.

It is noteworthy that the PCE2 solutions are not directly comparable to the usual/advanced refurbishments from the TABULA database because those refurbishments refer to a series of systematic renovations on every element of a building. Moreover, heating supply systems vary in different states from individual electrical heating equipment, heat pumps (such as a central heating system) and district heating with cogeneration.

4. Limitation and outlook

4.1. Volatility of costs

Uncertainties and inconsistencies in cost data are common dilemmas for a costing system. Many reasons can result in the volatility of cost, for example, time, area, availability of cost data, and the confidentiality of cost information.

In this study, cost data were collected along different times, and costs are highly area- and time-varying. In different areas and times, identical products may be of completely different value. Cost data in this study is based on a background of the Dutch market, while some less developed states may have higher availability of primary materials and cheaper labors. For example, according to a survey to the Keey Aerogel, the production cost of green aerogel can be reduced from 10 €/0.01 m^3 to 8 €/0.01 m^3 in some cheap-labor areas. Thus, the LCC results probably

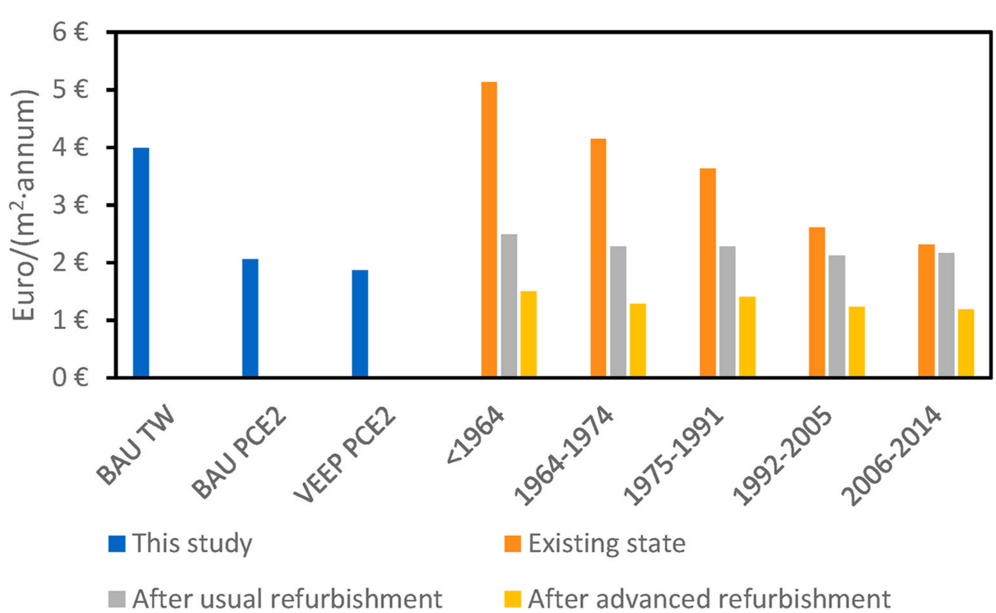


Fig. 8. Comparison of annual heating cost of scenarios in this study and five Dutch apartments constructed in different periods from TABULA database. Note: detailed description of existing state, and usual refurbishment, advanced refurbishment can be found in TABULA database [27].

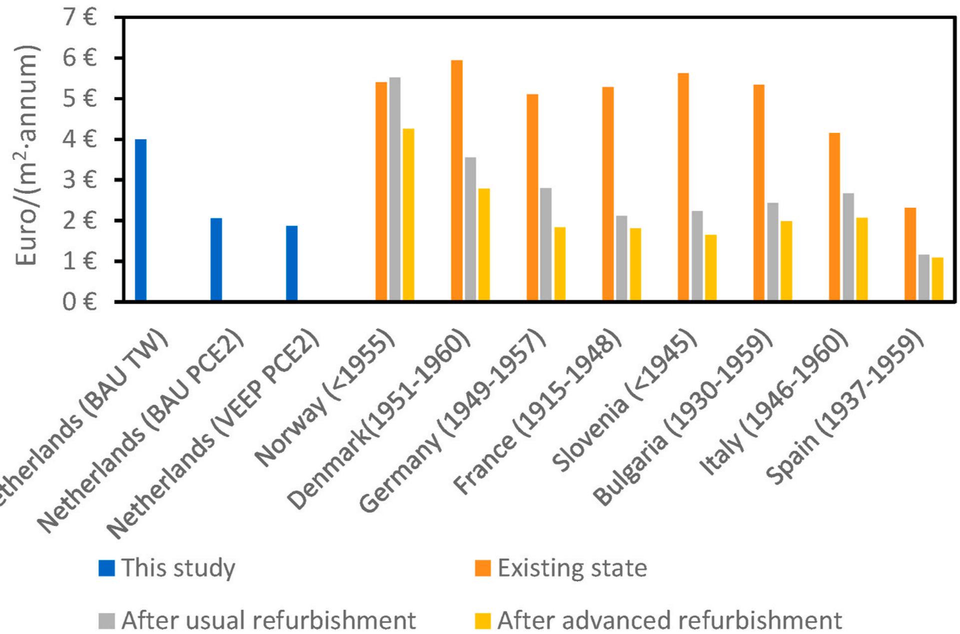


Fig. 9. Comparison of annual heating cost of scenarios in this study and typical apartments in different European countries from TABULA database. Note: detailed description of existing state, and usual refurbishment, advanced refurbishment can be found in in TABULA database [27].

only reflect the economic implication of the PCE2 system in developed areas.

It is noteworthy that due to its comparative and systemic nature, the LCC is not developed for accurate financial appraisal [17]. Rather than for precisely financial accounting, this LCC study more aims at cost management on identifying trade-offs in implementation of the VEEP PCE2, and comparing life cycle costs of alternatives, and reporting the potential cost optimizations.

4.2. Prices or costs

The distinction between prices and costs leads to the frequently asked question in LCC "whose costs is one accounting for?". This is original from the process of "value-added" in transactions, which has no counterpart in an LCA [28]. The cost of one actor (such as the consumer) is the revenue for another one (such as the PCE2 manufacturer). This is the reason why it is necessary to set up an actor or cost bearer in an LCC study to specify on which occasion costs or prices are used.

For example, for a consumer of the PCE2, the costs of ownership of PCE2 and costs of utilities such as electricity are market-related and do not reflect the true costs of material supply and electricity generation, but reflect the true costs that occur to the consumer. The difference between the price of the PCE2 and the production costs of PCE2 is the gross value added, which consists of profits, capital depreciation costs, and labor costs.

However, market prices and production costs are usually used equivalently in LCC, as in this study. Due to less availability of cost data, prices are usually more publicly accessible than costs. On the other hand, regarding product budgeting, detailed production costs substitute less detailed market costs.

4.3. Perspectives in LCC

The perspective of an LCC has always been a controversial issue. The perspective of a consumer is more suitable for this environmental LCC analysis as it seems able to cover a full life cycle of the VEEP PCE2 from production to disposal. The upstream actors, such as the manufacturer, deliver the reference flow to the consumer, and the downstream EoL actor treats the EoL reference flow for the consumer. Thus, an LCC from the consumer's perspective is about aggregating production costs and value-added from upstream and downstream activities. However, based on the supposition of the "rational person", consumers are only concerned by the costs of PCE2 acquisition and operational energy (and EoL costs if the consumer is responsible), and they are not interested in the exact detailed process of the production and EoL stage. Thus, production costs and EoL costs can be simplified as market prices or in the form of aggregated costs without specifying any details. As illustrated by Rebitzer and Hunkeler [28], if the perspective of an LCC is from the consumer, the costing process of other actors can be viewed as black boxes. The perspective of consumer LCC is unable for cost optimization because it cannot reflect on details of production costs and EoL costs.

This study is from the perspective of a consumer to seek strategies for cost optimization. However, there are two cost bearers in the costing system: the production and installation costs are incurred by the manufacturer; the operation and EoL costs are borne by the consumer. Fig. 10 takes the VEEP PCE2 scenarios as an example to illustrate the life cycle costs from a strict manufacturer's and consumer's perspective. Therefore, the LCC in this study is more likely to be deployed from a hybrid perspective of a manufacturer and a consumer: the manufacturer tries to reduce production costs of PCE2 to acquire maximum payoff while the consumer is paying higher prices, encouraging the manufacturer to reduce operation costs at the use stage.

Swarr et al. [29] presented a case study from a municipal perspective to ensure a transparent process. Even though it is not a strictly financial perspective, as it contains externalities, it unveils the possibility of a perspective that can aggregate all actors in the life cycle of a product. However, this reasoning still cannot tackle the preceding question "whose costs is one accounting for?". In our future study, we will try to conceive a method to explain the issue of perspective in LCC.

4.4. Standardization of LCC

Despite LCC having a longer history than LCA, it has not been standardized yet except for some specific uses. The emergence of variants of LCC further complicates its progress of standardization. For environmental LCC, the Code of Practice [29] by the SETAC did not present any concrete formula for steering its application, not to mention the societal LCC being at its infant stage. Moreover, the role of LCC was also

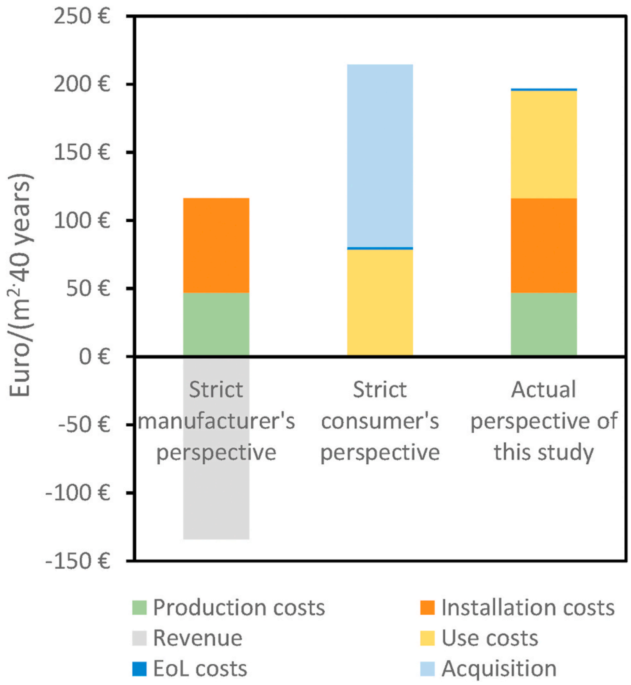


Fig. 10. Life cycle costs of VEEP PCE2 scenario from different perspectives. Note: strategies for cost optimizations are not included.

questioned as one main component for assessing economic sustainability in an overarching framework of the LCSA [30].

Studies were conducted on discussing the concept and practice of LCC [28,31–33], its variants [16,34,35], and its relation to LCSA [17,36–38]. Those studies did not effect a permanent cure but opened up a discussion on the need for a broad consensus on LCC. Thus, standardization of LCC has high significance for its theoretical clarification and practical application.

5. Conclusion

This study employed a prospective environmental LCC from a building owner/consumer's perspective to explore the economic performance and cost optimization strategies on the VEEP PCE2 system at an early stage in a Dutch context. We briefly introduced the environmental LCC according to SETAC's definition. The life cycle scope of the PCE2 system was defined as four stages according to EN 15804: (i) Production stage; (ii) Use stage; (iii) Installation stage; and (iv) EoL stage, with three comparable scenarios: the BAU TW, the BAU PCE2 and the VEEP PCE2. The findings reveal that the life cycle costs of VEEP PCE2 are 13% lower than that of the BAU PCE2, however 22% higher than that of the BAU TW Scenario. The production costs of VEEP PCE2 is 30% lower than that of BAU PCE2 due to the utilization of secondary raw materials. The operation costs account for around 70% of the life cycle costs in the BAU PCE2 and VEEP PCE2 scenario. Regarding VEEP PVE2, the three biggest three cost stressors are heating need costs (38% of the life cycle costs), installation costs (35%), and aerogel costs (20%), amounting to 93% of its life cycle costs.

Based on those main cost stressors, three cost-optimization strategies were evaluated: extension on the life span of the PCE2, full and partial reuse of PCE2 and cost-effective installation. The three strategies were aggregated to reflect the extent of cost optimization. Three levels of optimization were defined: low-level, medium-level and high-level. After medium-level optimization, the annual costs of BAU PCE2 and VEEP PCE 2 are lower than that of the BAU TW. After high-level optimization, the annual costs of VEEP PCE 2 are 1.42 €/annual lower than that of the BAU TW scenario, amounting to around 85 €/m^2 in 60 years.

To what extent the discount rate would affect the life cycle costs was modeled. The discount rate can significantly affect the LCC and even reverse its results. A negative discount rate is supposed to amplify the impact of operation costs on the life cycle costs, which enhances economic advantages for those products which have lower operation costs. In addition, the potential costs for the implementation of the VEEP PCE2 system in the Netherlands for different cohorts of the buildings, as well as in other EU MSs were compared.

Finally, limitations and conceptual debates of LCC were addressed. Uncertainties and inconsistencies in cost data and the mixed-usage of prices and costs are the most common dilemmas that may result in uncertainty to life cycle costs. The perspective of actors is a long-standing issue in LCC. Even though environmental LCC can use a multi-actor perspective, it still cannot answer the question "whose costs is one accounting for?". Thus, standardization of LCC has high significance for its theoretical clarification and practical application.

CRediT authorship contribution statement

Chunbo Zhang: Conceptualization, Methodology, Software, Investigation, Writing - original draft, Formal analysis. **Mingming Hu:** Conceptualization, Investigation, Writing - review & editing, Supervision. **Benjamin Laclau:** Validation, Resources, Software, Data curation. **Thomas Garnesson:** Validation, Resources, Software, Data curation. **Xining Yang:** Validation, Visualization. **Chen Li:** Validation, Visualization. **Arnold Tukker:** Writing - review & editing, Supervision.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jobe.2020.102002.

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