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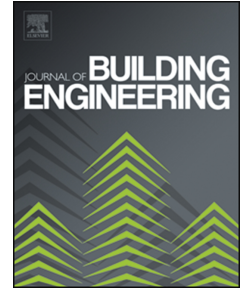
Citation

Zhang, C., Hu, M., Laclau, B., Garnesson, T., Yang, X., Li, C., & Tukker, A. (2020). Environmental life cycle costing at the early stage for supporting cost optimization of precast concrete panel for energy renovation of existing buildings. *Journal Of Building Engineering*, 35, 102002.
doi:10.1016/j.jobe.2020.102002

Version: Not Applicable (or Unknown)
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Downloaded from: <https://hdl.handle.net/1887/3133404>

Note: To cite this publication please use the final published version (if applicable).

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PII: S2352-7102(20)33634-2

DOI: <https://doi.org/10.1016/j.jobe.2020.102002>

Reference: JOBE 102002

To appear in: *Journal of Building Engineering*

Received Date: 17 August 2020

Revised Date: 18 October 2020

Accepted Date: 7 November 2020

Please cite this article as: C. Zhang, M. Hu, B. Laclau, T. Garnesson, X. Yang, C. Li, A. Tukker, Environmental life cycle costing at the early stage for supporting cost optimization of precast concrete panel for existing building retrofit, *Journal of Building Engineering*, <https://doi.org/10.1016/j.jobe.2020.102002>.

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CRedit author 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

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1 Environmental life cycle costing at the early stage for 2 supporting cost optimization of precast concrete panel 3 for existing building retrofit

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13 Abbreviations

14 ADR Advanced dry recovery technology
15 BAU Business-as-usual
16 CDW Construction and demolition waste
17 CRLWCA Coarse recycled lightweight concrete aggregate
18 DGR Dry grinding & refining system
19 EC European Commission
20 EED Energy Efficiency Directive
21 EoL End-of-life
22 EPBD Energy Performance of Buildings Directive
23 EPS Expandable polystyrene
24 EU European Union
25 FRLWCA Fine recycled lightweight concrete aggregate
26 HAS Heating-air classification system
27 LCA Life cycle assessment
28 LCC Life cycle costing
29 LCSA life cycle sustainability assessment
30 MS Member State of the EU
31 NECP National Energy and Climate Plan
32 NEEAP National Energy Efficiency Action Plans
33 PCE Prefabricated concrete element
34 PCE1 Prefabricated concrete element for new buildings
35 PCE2 Prefabricated concrete element for existing buildings

36 RFUA Recycled fiber wool ultrafine admixture
37 RGUA Recycled glass ultrafine admixture
38 SETAC Society of Environmental Toxicology and Chemistry
39 URLWCA Ultrafine recycled lightweight concrete aggregate
40 VEEP European Union Horizon 2020 project VEEP
41

42 Abstract

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

60 **Keyword:** life cycle costing (LCC); construction and demolition waste (CDW); building retrofit;
61 recycling; prefabricated concrete element, energy efficiency

62

63 1. Introduction

64 The building sector is responsible for 36% of CO₂ emissions and 40% of energy consumption in the
65 European Union (EU), and almost three-quarters of the buildings in Europe are energy-inefficient [1].
66 Directives at EU level have been enacted for cost-effective renovation of buildings. In 2010 the EC
67 enacted the revision of the Energy Performance of Buildings Directive (EPBD, 2010/31/EU) aiming
68 to optimize the energy efficiency of the EU buildings by the cost-effectiveness of energy efficiency
69 measures [2]. The Energy Efficiency Directive (EED, 2012/27/EU) states in Article 4 that Member
70 States (MS) shall establish a long-term strategy for mobilizing investment in the renovation of the
71 building stock [3].

72 As a Member State of the EU, the Netherlands was requested to draw up national energy efficiency
73 plans. For instance, The EED states in Article 24 that Member States (MSs) shall submit National
74 Energy Efficiency Action Plans (NEEAP) which cover energy efficiency optimization measures and
75 expected and/or achieved energy savings by 2014, and every three years thereafter [3]. The fourth
76 NEEAP for the Netherlands was drafted by the Minister of Economic Affairs and the Minister of the
77 Interior and Kingdom Relations in the Netherlands as part of the obligation to report to the NEEAP
78 [4]. For the period from 2021-2030, each EU MS was also required to draft a National Energy and
79 Climate Plan (NECP) indicating methods to achieve a series of targets by 2030 [5]. The Dutch
80 building renovation strategy is mainly based on the Energy Agreement for Sustainable Growth [6],
81 which includes plans on energy conservation in the built environment. According to the Netherlands
82 Environmental Assessment Agency, to respond to energy efficiency ambitions in those plans, the
83 Netherlands committed to an energy-neutrality target within the Dutch built environment by 2050.
84 This means of 7.5 million dwellings, 80% are to be renovated to energy-neutral levels by 2050,
85 which indicates 170,000 homes are to be renovated per annum [7].

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

101 The PCE2 system is at its designing stage, so it is unclear whether the application of this PCE2
102 system will necessarily provide an improvement in overall economic benefits along the life span of a
103 building. The goal of this study is at an early stage from the consumer's perspective to compare the
104 economic viability and associated optimizing strategies of a wall of building refurbished with the
105 VEEP PCE2 to the wall of building refurbished with the business-as-usual (BAU) PCE2, and to the
106 wall of building without refurbishment under the context of an EU MS the Netherlands. Thus, this
107 study aims to answer the following research questions, from an empirical aspect: 1) whether the use
108 of PCE leads to an economic advantage over a specific life cycle of an existing building; 2) what is
109 the biggest cost stressor in the life cycle of a PCE2? 3) the potential route for further cost
110 optimization; and 4) how would the discount rate affect the life cycle costs, especially when some

111 European countries have entered a negative rate era? A virtual apartment in Europe is selected for
112 dynamic thermal simulation, in which the heating and cooling energy demands before and after
113 refurbishment with PCE2s will be evaluated. By employing environmental life cycle costing (LCC),
114 the life cycle economic performance of the apartment refurbished with or without PCE2 over 40
115 years was investigated, and associated strategies for cost optimizations were introduced. In addition,
116 the potential costs for the implementation of the VEEP PCE2 system in the Netherlands for different
117 cohorts of the buildings, as well as in other EU MSs, were compared.

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

121 2. Methods and materials

122 2.1 Environmental life cycle costing

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

129 Environmental LCC was initially defined by Rebitzer et al. [17] as an LCA-based LCC method,
130 which utilizes an LCA model as a basis to estimate incurred costs in a product assessment. The
131 Society of Environmental Toxicology and Chemistry (SETAC) Europe working group on LCC
132 formally categorized LCC into: (i) conventional LCC which only includes internal costs; (ii)
133 environmental LCC which includes internal costs and external costs expected to be internalized; and

134 (iii) societal LCC which contains internal, plus all external, costs [18]. Additionally, Hoogmartens et
135 al. [16] explain an uncommonly accepted concept, namely full environmental LCC, which extends
136 environmental LCC with monetized, non-internalized environmental costs as societal LCC does.

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

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

149 2.2 Goal and scope definition

150 2.2.1 Goal and scope

151 The goal of this study is to compare the financial profitability and optimization potentials of
152 manufacturing, and using the BAU PCE2 and VEPP PCE2 as an over-cladding façade of the existing
153 building compared to the original wall of building without any refurbishment. Both BAU and VEPP
154 PCE2 are expected to be preferentially implemented to those obsolete buildings constructed before
155 1960. The environmental LCC only accounts for internal costs, which usually consists of production
156 budgets and transfers (such as taxes, subsidies and fees). LCA was not performed, thus external costs
157 are not considered.

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

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

169

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

170

171 The production stage includes two procedures, which are raw material production, and PCE2
 172 manufacturing. In the process of raw material production, raw materials will be prepared for the
 173 fabrication of the PCE2, including raw materials for lightweight concrete (expanded clay, sand,
 174 plasticizer, etc.), ferrous frame, and insulation layer. Both primary and secondary raw materials will
 175 be incorporated into the production of green lightweight concrete and green aerogel for further
 176 manufacturing of the VEEP PCE2. In the process of PCEs manufacturing, a sandwich panel will be

177 fabricated with the mentioned raw materials. At the use stage, the PCE2 will be transported to the
178 construction site for installation. Then dynamic thermal simulations is performed to compare the
179 heating and cooling energy demands of a virtual apartment block with or without refurbishment of
180 the PCE2 in the capital of the Netherlands, Amsterdam. At the EoL stage, the PCE2 will be
181 dismantled and disposed.

182

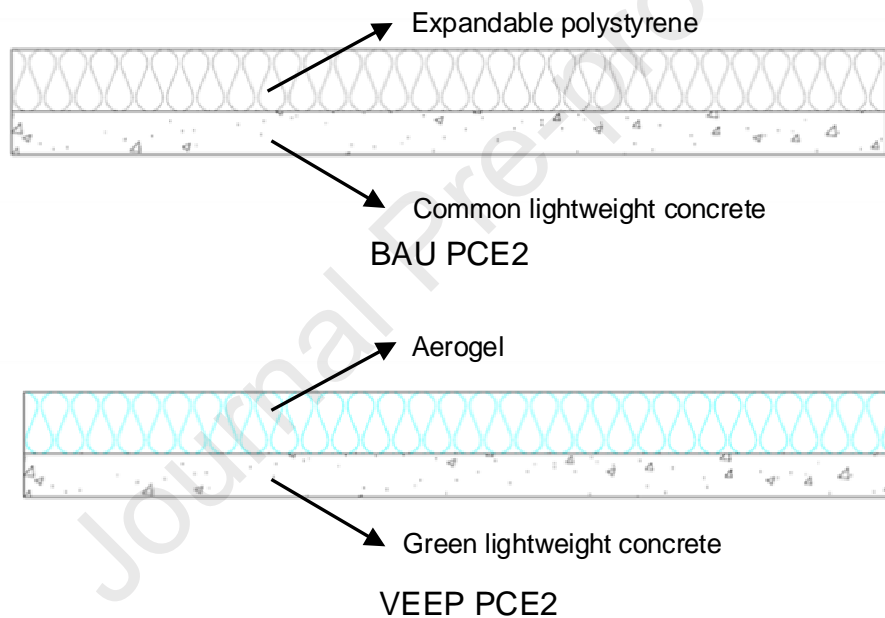
183 2.2.2 Scenario development

184 Based on the defined scope, three scenarios were developed in this study: (i) BAU TW, (ii) BAU
185 PCE2, and (iii) VEPP PCE2. The BAU TW scenario denotes the building uses the traditional wall as
186 façade without refurbishment. The reference building is assumed to be constructed between 1941 to
187 1960. Based on the statistic from the Buildings Performance Institute Europe [21], the thermal
188 transmittance (U-value) of the external walls for the target building group in the Netherlands is
189 assumed $2.70 \text{ W}/(\text{m}^2\cdot\text{K})$ for the thermal simulation in this study. Regarding the economic assessment
190 of the BAU TW scenario, cost occurs only at the use stage.

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

199 The VEPP PCE2 scenario describes the building with the traditional wall in BAU TW be retrofitted
200 with the VEPP PCE2. Compared to the BAU PCE2, the VEPP PCE2 has higher resource efficiency

201 due to incorporated secondary raw materials. The VEEP PCE2 uses green aerogel with high thermal
 202 performance as the insulation layer. The thermal conductivity of the aerogel for the PCE2 is set as
 203 0.0157 W/(m.K). The green lightweight concrete also contains secondary raw materials such as
 204 secondary coarse and fine aggregate, and secondary contentious particle, amounting to more than 57%
 205 of lightweight concrete by weight. The U-value of the traditional wall refurbished with VEEP PCE2
 206 is 0.203 W/(m²K). Regarding the life cycle costs of the VEEP PCE2, costs are incurred in four life
 207 cycle stages. Further introduction of the VEEP PCE2 system can be found in the supplementary
 208 document.



209
 210 Figure 1 Cross-sectional views of BAU PCE2 (above) and VEEP PCE2 (below). Note: BAU PCE2 and VEEP PCE2
 211 share the same dimension: length 2000 mm, width 2000 mm, thickness 130 mm.

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213 2.2.3 Functional unit

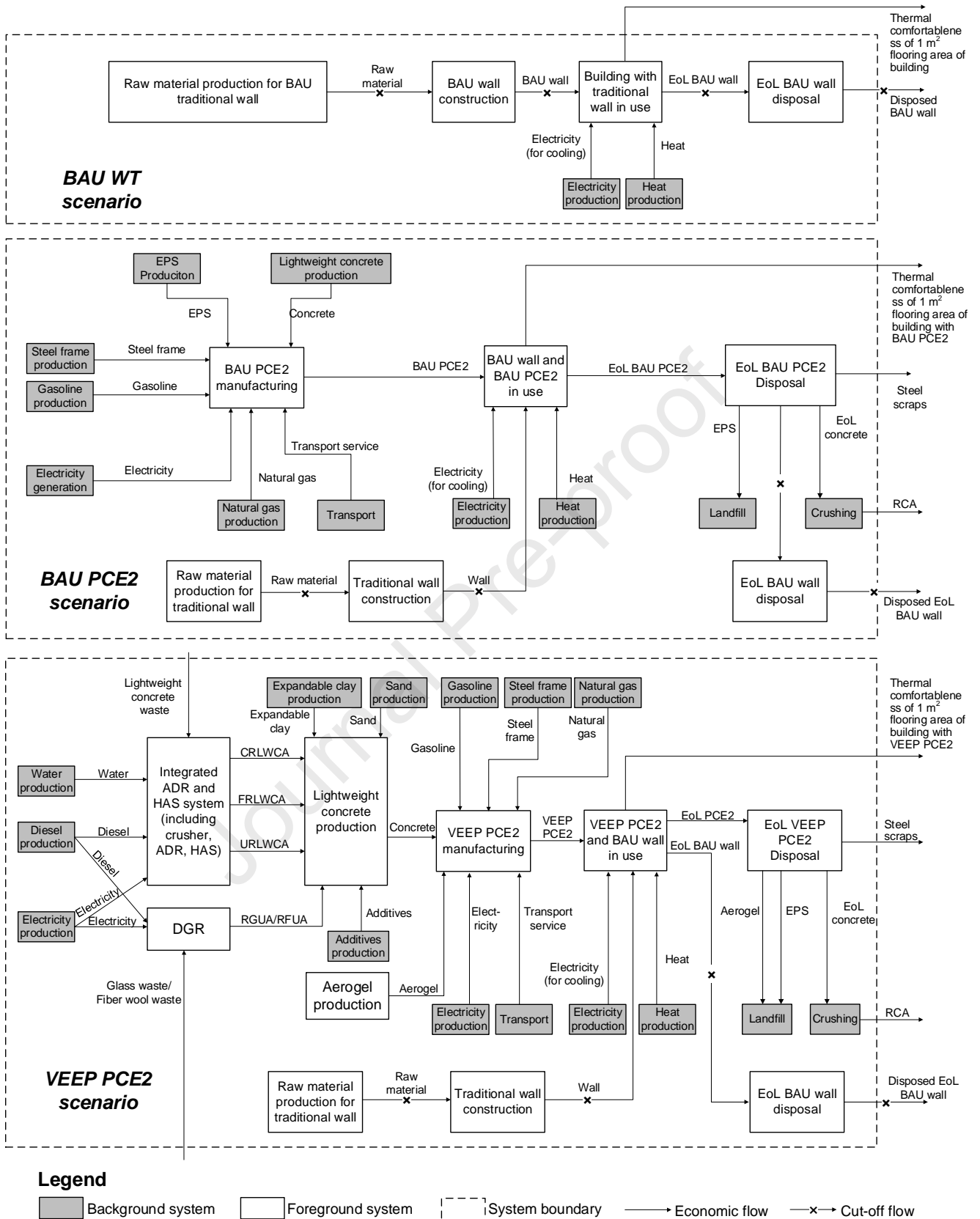
214 In the BAU PCE2 and PCE PCE2 scenario, it is assumed that the required building façade per 1 m²
 215 of flooring area amounts to 0.55 m² of PCE2. The functional unit is set as: maintaining the thermal
 216 comfortableness of 1 m² flooring area of a building (with or without the implementation of the PCE2
 217 system for refurbishment) and active heating and cooling for 40 years based on the climatic
 218 condition of Amsterdam.

219

220 2.3 Life cycle economic inventory analysis

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

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226 Figure 2 System boundaries for the BAU TW scenario (above), the BAU PCE2 scenario (middle), and the VEEP PCE2
 227 scenario (below). Note: ADR represents Advanced Dry Recovery system; BAU denotes business-as-usual; CRLWCA
 228 represents coarse recycled lightweight concrete aggregate; DGR indicates Dry Grinding & Refining system; EoL
 229 represents end-of-life; EPS: expandable polystyrene; FRLWCA denotes Fine lightweight recycled concrete aggregate;

230 HAS represents Heating-Air Classification System; PCE2 represents prefabricated concrete element for building retrofit;
231 RGUA represents recycled glass ultrafine aggregate; URLWCA represents Ultrafine recycled lightweight concrete
232 aggregate; VEEP represents European Union Horizon 2020 project VEEP.

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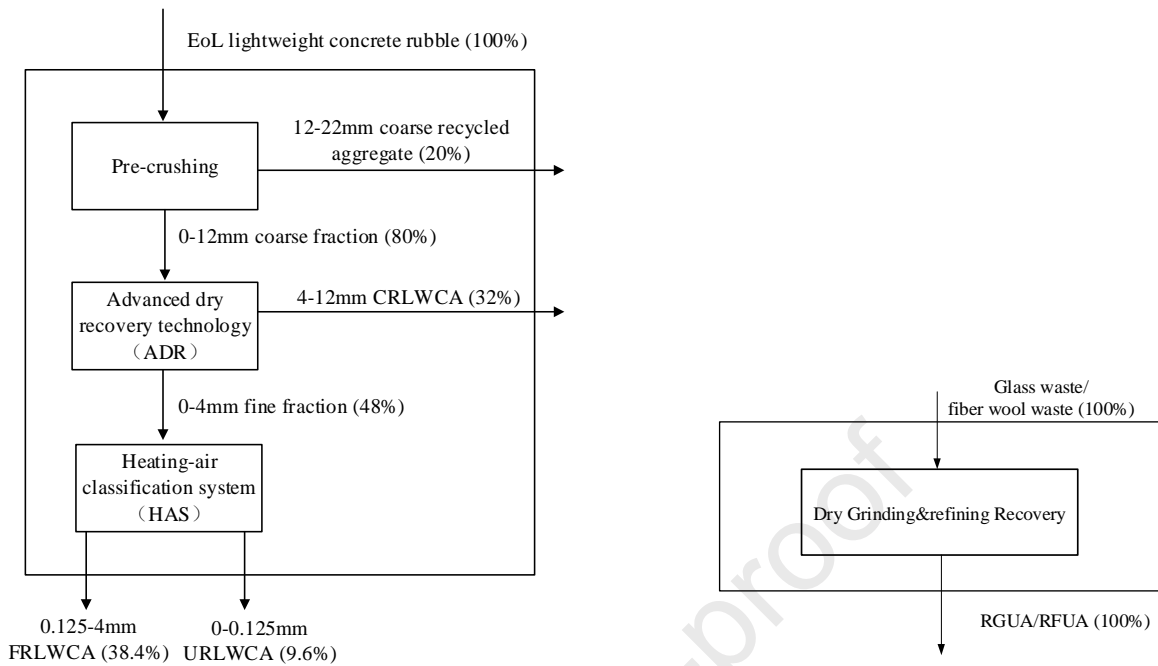
234 In a national accounting system, internal costs can be measured either in market prices: adding all
235 expenditure on products, or by adding all factor costs [18]; the latter are market prices excluding
236 transfers. However, for an LCC study, market prices and factor costs are used in a mixed manner. It
237 is difficult and incorrect to use market prices and factor costs alone, and the reason will be elaborated
238 later in 4.2. The cost information was collected via Ecoinvent cost database 3.4 for OpenLCA 1.9,
239 surveys by email and telephone and literature.

240

241 2.3.1 Production stage

242 In the VEEP PCE2 scenario, EoL lightweight concrete is recycled by the integrated advanced dry
243 recovery (ADR) and heating-air classification system (HAS) technology for the production of
244 ultrafine recycled lightweight concrete aggregate (URLWCA), fine recycled lightweight concrete
245 aggregate (FRLWCA) and coarse recycled lightweight concrete aggregate (CRLWCA), as illustrated
246 in Figure 3. The dry grinding and refining system (DGR) can process glass/fiber wool waste into
247 recycled glass ultrafine admixture (RGUA) and recycled fiber wool ultrafine admixture (RFUA) as
248 depicted in Figure 3. The mass balance for ADR and HAS processing normal-weight siliceous
249 concrete and for DGR was discussed in the previous study [8,11], based on which integrated unit
250 costs (including waste transport raw material production, utilities, personnel, equipment) of
251 URLWCA, FRLWCA, CRLWCA, RGUA, RFUA were determined. As can be seen from Figure 3
252 that mass balance varies between processing lightweight and normal-weight concrete. However, the
253 integrated unit costs of the coarse, fine, ultrafine fraction from processing lightweight concrete are
254 identical to those materials made from normal-weight concrete due to the mass-based allocation
255 scheme. The cost information for the production stage is presented in the supplementary document.

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Figure 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.

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2.3.2 Installation stage

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

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2.3.3 Use stage

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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

275 boiler. With respect to cooling, cooling energy need is modified into the electricity demand of the air
 276 conditioning based on an energy efficiency ratio. The seasonal energy efficiency ratio for household
 277 air conditionings in DIN V 18599 is set as 4.7 [22]. The annual demand for heating and cooling of
 278 three scenarios are shown in Table 2. Other details of the dynamic thermal stimulation are elaborated
 279 in the supplementary document.

280 Table 2 Heating and cooling demand of three scenarios

	BAU TW	BAU PCE2	VEEP PCE2
	kWh/(m ² ·year)	kWh/(m ² ·year)	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

281

282 2.3.4 End-of-life stage

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

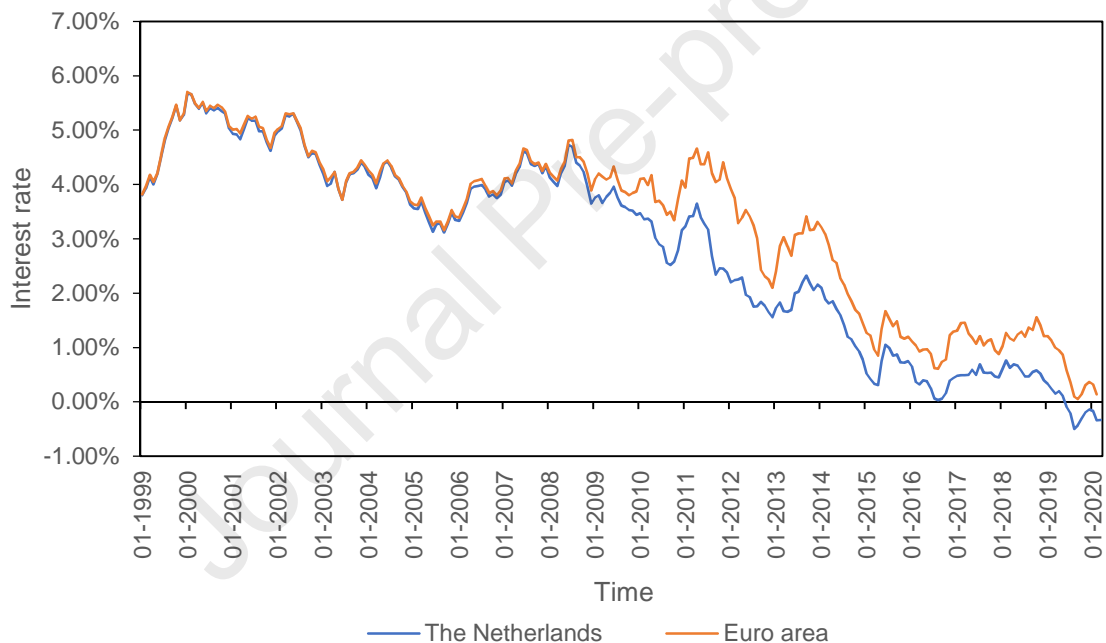
291 2.4 Life cycle economic impact assessment

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

294 Regarding cost categorization, there are commonly three ways: expenditure-based, actor-based and
 295 life cycle-based [8]. Since integrated unit costs were used, cost information is not specific and
 296 detailed enough to be broken down from an expenditure aspect. The perspective of the consumer was
 297 used, and two cost bearers exist in the LCC, namely manufacturer and consumer. There is only one

298 main actor in each life cycle stage, thus, actor-based and life cycle-based will be identical. Therefore,
 299 a life cycle-based cost breakdown structure was applied. Costs incurred along the life cycle is
 300 categorized into production costs, operation costs and EoL cost.

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



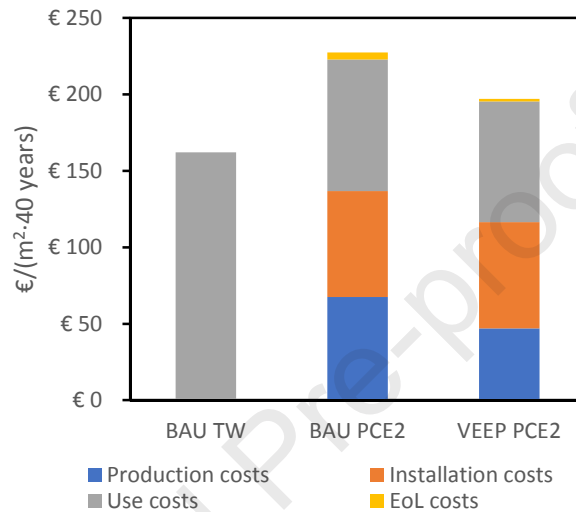
306 Figure 4 Time-series interest rate for the Netherlands and Euro area, data from De Nederlandsche Bank [23]
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309 3. Results and interpretation

310 3.1 Life cycle costs of three scenarios

311 The results of the LCC from a consumer perspective are shown in Figure 5. The life cycle costs of
 312 the VEEP PCE2 is 13% lower than that of the BAU PCE2, however 22% higher than that of the
 313 BAU TW Scenario. The operation costs account for around 70% of the life cycle costs of the BAU

314 PCE2 and VEEP PCE2 scenario, while the EoL costs are almost negligible. Due to the utilization of
 315 secondary raw materials, the production costs of the VEEP PCE2 are 30% lower than that of BAU
 316 PCE2. Regarding the VEEP PVE2, the three biggest cost stressors are heating costs (38% of the life
 317 cycle costs), installation costs (35%), and aerogel costs (20%), amounting to 93% of the life cycle
 318 costs.



319 Figure 5 Life cycle costs of BAU TW, BAU PCE2, VEEP PCE2 scenario
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322 3.2 Strategies on cost optimizations

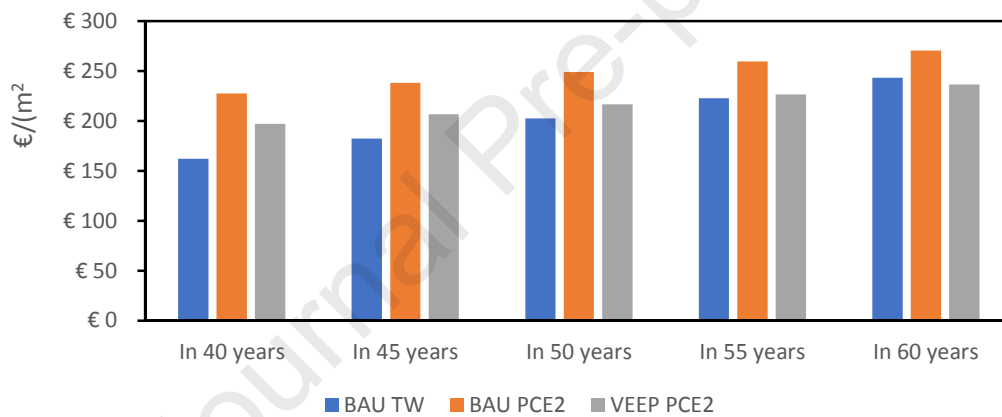
323 Considering those three main cost elements, relevant cost-optimization strategies are: extension on
 324 the life span of PCE2, full and partial reuse of PCE2 and cost-effective installation.

325 3.2.1 Service lifetime of PCE2

326 The heating demand of the BAU PCE2 and VEEP PCE2 scenario is directly determined by their
 327 thermal performance. Adjusting the structure of PCE2, for instance by increasing the thickness of the
 328 aerogel layer, can lower the U-value of PCE2, however this increases the production costs as well.
 329 Reducing the heating demand by modifying the structure of a PCE2 is a complicated systematic
 330 engineering process. It is assumed the dimensions of the aerogel layer of the PCE2 already reached

331 an optimum condition and alteration on the thickness of the insulation layer is omitted from this
 332 study.

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

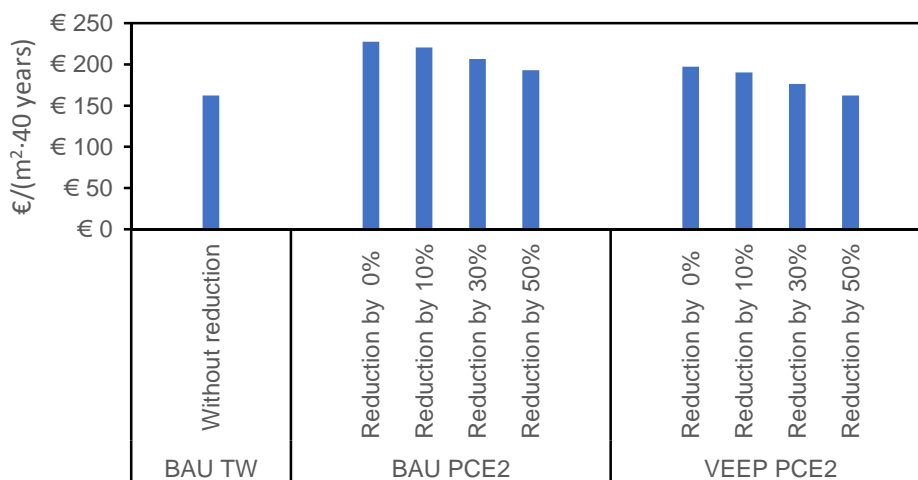


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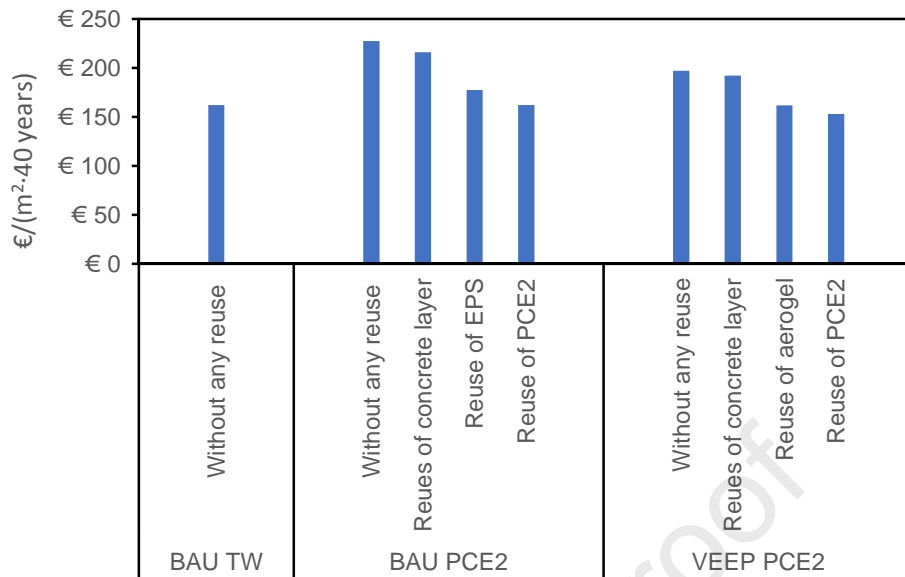
(a) Comparison of life cycle costs of three scenarios in different lifetimes



343

344

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

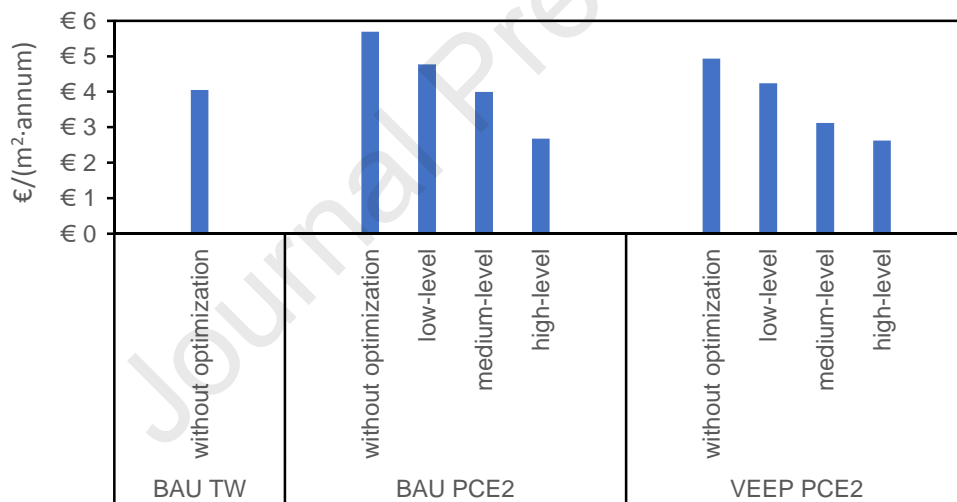


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(c) Comparison of scenarios with or without reuse of wastes



348

349

350

351

352

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

Figure 6 Results of the cost optimization strategies

353

3.2.2 Installation of PCE2 with novel anchoring systems

354

If a connection/joint between PCEs is considered permanent, such as welded connections, adhesive

355

anchors or grouting or dry packing of connections, then PCEs cannot be separated and disassembled

356

into individual elements without any damages. If the installation systems for PCE2 consist of the

357

HALFEN system, which allows a quick, flexible and simple installation, PCE2 can also be easily

358 disassembled and detached from the old structure/wall at its EOL stage for reuse. Over 90% of the
359 installation costs result from personnel costs. As the dismantlable anchoring solution is expected to
360 a large degree reduce the labor-hours during the installation of PCEs, it is assumed 10%, 30% and 50%
361 of the installation costs can be reduced in BAU PCE2 and VEEP PCE2 scenarios. The modified life
362 cycle costs of each scenario are presented in Figure 6 (b).

363 3.2.3 Reusability of PCE2

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

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

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

378 10% of physical loss is assumed in the process of reuse, and the loss fraction is compensated by
379 production. Additional costs incurred during the process of reuse are included in the physical loss.
380 The life cycle costs of PCE scenarios with or without reuse are presented in Figure 6 (c). It can be
381 seen that the reuse of insulation materials has a considerably positive effect on cost reduction, while

382 the reuse of the concrete layer barely affects the life cycle costs. For the VEEP PCE2, its life cycle
 383 costs can be decreased to €163 if the aerogel layer of the PCE2 is successfully reused.

384

385 3.2.4 Aggregation of cost optimizations

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

389

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

390

391 Due to different time spans in each level, the reductions in life cycle costs cannot be directly
 392 compared. Therefore, the result of LCC is expressed in the form of annual value. As it is depicted in
 393 Figure 6 (d) after medium-level optimization the annual costs of BAU PCE2 and VEEP PCE 2 is
 394 lower than that of the BAU TW scenario. After high-level optimization, the annual costs of the
 395 VEEP PCE2 is 1.42 €/annual lower than that of the BAU TW scenario, amounting to around 85 €/m²
 396 in 60 years.

397

398 3.3 Effect of discount rate

399 To what extent the fluctuation of the discount rate would affect the life cycle costs is explored.
 400 Applying a discount rate to an LCC analysis depends on specific research questions to be answered.
 401 For example, the discount rate ranges from 2% in long-term public projects, and 5-15% in private
 402 investments, to 20% in the high-tech area [18]. Since in this study the operation cost is borne by
 403 individual consumers, the discount rate is related to the interest rate in Figure 4. A range of (-1%,3%)
 404 is assumed to model the fluctuation of the life cycle costs responding to discount rates. The BAU
 405 TW, BAU PCE2 with medium-level optimization and VEEP PCE2 with medium-level optimization

406 are selected as examples under a 54-year service lifetime. The annual energy cost and EoL cost are
 407 discounted according to Formula (1) and (2).

408

$$409 \quad C_p^t = \frac{C_{heating} + C_{cooling}}{(1+r)^t} \quad (1)$$

$$410 \quad C_p^{EoL} = \frac{C_{EoL}}{(1+r)^{54}} \quad (2)$$

411

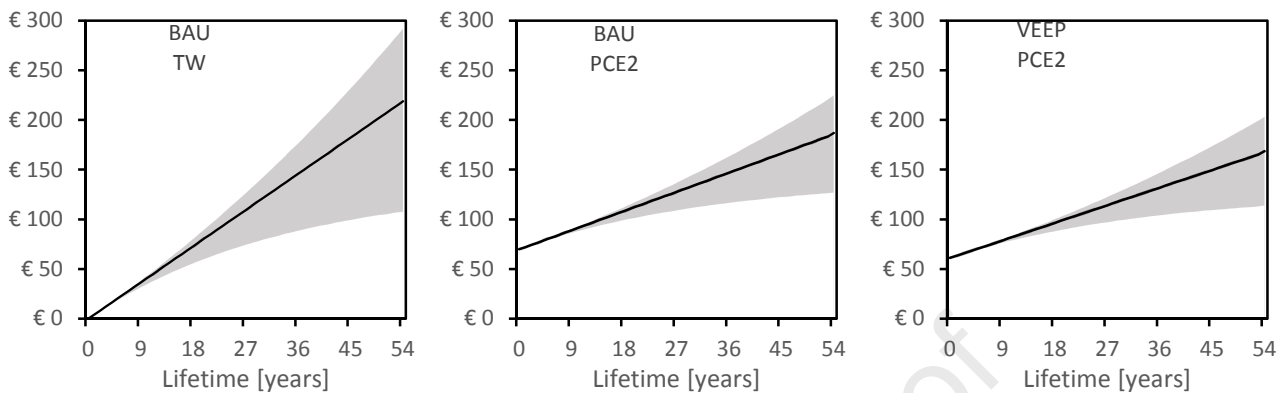
412 Where C_p^t denotes the net present value of the heating and cooling costs incurred at t year; $C_{heating}$
 413 represents annual heating costs; $C_{cooling}$ indicates annual cooling costs; r denotes discount rate;
 414 C_p^{EoL} represents the net present value of the EoL costs incurred at the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

416

417 The life cycle costs of three scenarios with different discount rates are shown in Figure 7. It can be
 418 seen from the trend that a negative discount rate will increase life cycle costs over time, while
 419 positive discount rates are supposed to lower it. Regarding PCE2 scenarios, there is an obvious trade-
 420 off on additional production costs and lower operation costs. The negative discount rate will amplify
 421 the impact of operation costs on the life cycle costs, which enhances the economic advantage for
 422 VEEP PCE2 which has lower operation costs. For example, when the average discount rate descends
 423 from 0% to -1% over a 54-year time span, the reduction of the life cycle cost of VEEP PCE2
 424 (medium-level) increases from €50 to €88 compared to BAU TW. As Europe has entered an era of
 425 a negative discount rate, using insulation with high thermal performance such as aerogel is likely to
 426 be more competitive in the future market building retrofit.

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

433 BAU TW in a static-state costing system, but €6 higher if the average discount rate remains 3% over
 434 54 years.



435
 436 Figure 7 Life cycle costs of the BAU TW, BAU PCE2 with medium-level optimization, VEEP PCE2 with medium-level
 437 optimization under 54-year service lifetime. Note: The minimum limit of life cycle costs was estimated by assuming 3%
 438 as the average discount rate; the maximum limit of life cycle costs was estimated by assuming -1% as the average
 439 discount rate; the line inside the shaded area represents static-state life cycle costs without discounting. The
 440 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
 441 is 126.97 /186.77/224.60 €; the min/med/max life cycle costs of BAU PCE2 is 113.59/168.56/203.21 €.

442

443 3.4 Comparison with results to other studies

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

448 $TS = ((\text{"life cycle cost"} \text{ OR } LCC \text{ OR } \text{"life cycle costing"}) \text{ AND } (\text{residential building}) \text{ AND } (\text{wall* OR}$
 449 $\text{façade* OR envelope*})) \quad (3)$

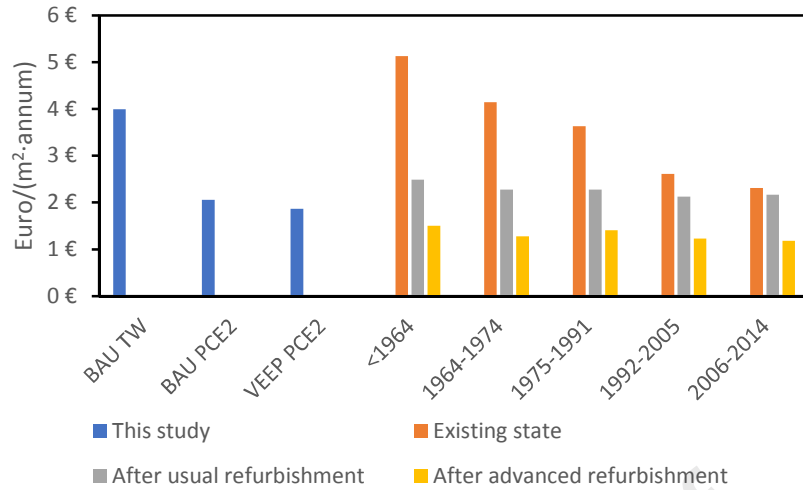
450 After reviewing those literature, however, it is difficult to compare the results of this study with other
 451 LCC cases due to the diversity of modeling approaches, settings and purposes, and peculiarity in
 452 technologies selected and local characteristics. To put the study in context, a comparison analysis has
 453 been carried out. The potential costs for the implementation of the VEEP PCE2 system in the
 454 Netherlands for different cohorts of the buildings, as well as in other EU Member States are

455 calculated. Because energy costs for cooling are almost negligible in the climatic condition of the
456 Netherlands, the comparison focuses on the energy demand for heating.

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

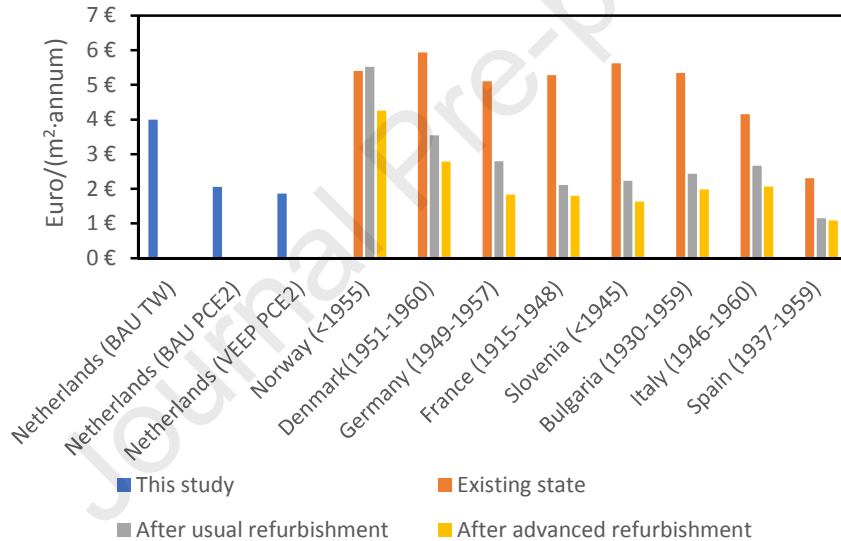
463 From a cross-state comparison of annual heating costs in Figure 9, the VEEP PCE2 solution can be
464 seen as advanced refurbishment in some middle-latitude states such as Germany or France. However,
465 this may be because the annual heating demand of the basic reference BAU TW is lower than the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

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



476

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



480

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

484

485 4. Limitation and outlook

486 4.1 Volatility of costs

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

490 In this study, cost data were collected along different times, and costs are highly area- and time-
491 varying. In different areas and times, identical products may be of completely different value. Cost
492 data in this study is based on a background of the Dutch market, while some less developed states
493 may have higher availability of primary materials and cheaper labors. For example, according to a
494 survey to the Keey Aerogel, the production cost of green aerogel can be reduced from 10 €/0.01 m³
495 to 8 €/0.01 m³ in some cheap-labor areas. Thus, the LCC results probably only reflect the economic
496 implication of the PCE2 system in developed areas.

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

501 4.2 Prices or costs

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

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

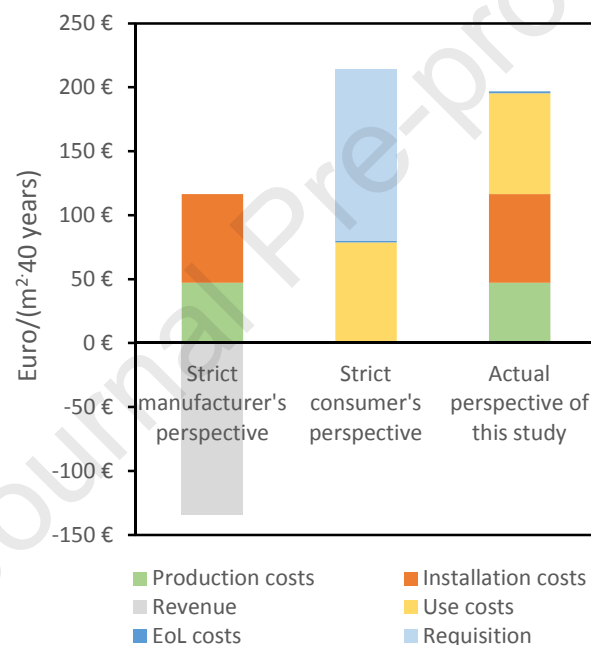
512 However, market prices and production costs are usually used equivalently in LCC, as in this study.
513 Due to less availability of cost data, prices are usually more publicly accessible than costs. On the
514 other hand, regarding product budgeting, detailed production costs substitute less detailed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

516

517 4.3 Perspectives in LCC

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

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



539

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

542

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

548 4.4 Standardization of LCC

549 Despite LCC having a longer history than LCA, it has not been standardized yet except for some
550 specific uses. The emergence of variants of LCC further complicates its progress of standardization.
551 For environmental LCC, the Code of Practice [29] by the SETAC did not present any concrete
552 formula for steering its application, not to mention the societal LCC being at its infant stage.
553 Moreover, the role of LCC was also questioned as one main component for assessing economic
554 sustainability in an overarching framework of the LCSA [30].

555 Studies were conducted on discussing the concept and practice of LCC [28,31–33], its variants
556 [16,34,35], and its relation to LCSA [17,36–38]. Those studies did not effect a permanent cure but
557 opened up a discussion on the need for a broad consensus on LCC. Thus, standardization of LCC has
558 high significance for its theoretical clarification and practical application.

559 5. Conclusion

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

571 cycle costs), installation costs (35%), and aerogel costs (20%), amounting to 93% of its life cycle
572 costs.

573 Based on those main cost stressors, three cost-optimization strategies were evaluated: extension on
574 the life span of the PCE2, full and partial reuse of PCE2 and cost-effective installation. The three
575 strategies were aggregated to reflect the extent of cost optimization. Three levels of optimization
576 were defined: low-level, medium-level and high-level. After medium-level optimization, the annual
577 costs of BAU PCE2 and VEPP PCE 2 are lower than that of the BAU TW. After high-level
578 optimization, the annual costs of VEPP PCE 2 are 1.42 €/annual lower than that of the BAU TW
579 scenario, amounting to around 85 €/m² in 60 years.

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

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

592 Acknowledgment

593 The authors appreciate the financial support from the EU H2020 project VEPP “Cost-Effective Recycling of
594 CDW in High Added Value Energy Efficient Prefabricated Concrete Components for Massive Retrofitting of

595 our Built Environment” (No. 723582). Chunbo Zhang received funding from the China Scholarship Council
596 (201706050090). The authors also appreciate the following VEEP project partners for their help in data
597 collection: Arianna Amati from RINA Consulting, Dr. Francisco Ruiz from Keey Aerogel, Mr. Ismo Tiihonen,
598 Dr. Jaime Moreno Juez from Technalia, Dr. Abraham Teklay Gebremariam and Dr. Francesco Di Maio from
599 the Delft University of Technology, Mr. Frank Rens and Mr. Eric van Roekel from Strukton BV.

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Highlights

- Innovative technological systems for recycling construction and demolition waste (CDW) were introduced;
- A resource-efficient prefabricated concrete element (PCE2) system for refurbishing existing building were presented;
- Economic implications on building renovation via prefabrication panel that included secondary raw materials are presented;
- The long-stand conceptual debates of environmental LCC were addressed.

Declaration of interests

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.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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