Towards circular and energy-efficient management of building stock: an analysis of the residential sector of the Netherlands

Zhang, C.

Chapter 3

Life cycle greenhouse gas emission and cost analysis of prefabricated concrete elements for use as façade of new building

Chunbo Zhang, Mingming Hu, Xining Yang, Arianna Amati, Arnold Tukker

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Abstract

Buildings are responsible for approximately 36% of carbon emissions in the European Union. Besides, gradual aging and a lack of adaptability and flexibility of buildings often lead to destructive interventions, resulting not only in higher costs but also in a large amount of construction and demolition waste (CDW). Recently, an innovative system (Ref. VEEP project) has been developed to recycle CDW for the manufacturing of energy-efficient prefabricated concrete elements for new building construction (PCE-new). By applying life cycle costing (LCC) and life cycle assessment (LCA), this study aimed to determine whether the use of VEEP green PCE-new leads to lower carbon emission and lower associated costs over the life cycle of an exemplary four-story residential building in the Netherlands than a business-as-usual (BAU) PCE-new scenario. This paper provides a case study on the alignment and/or integration of LCA and LCC in an independent and a combined manner (via monetization). This study examines how the internalization of carbon emission and discount rate will affect the final life cycle costs over a 120-year life span. The findings are that the key to the economic viability and environmental soundness of green PCE-new is to improve its thermal transmittance. Besides, internalization of external cost can monetarize the environmental advantage, thus, slightly expanding the cost advantage of low carbon options but also leading to larger uncertainty about the LCC result.

Keywords: life cycle costing, life cycle assessment, prefabricated concrete element, building façade, construction and demolition waste (CDW), industrial ecology.

Abbreviations

ADR	Advanced drying recovery technology
BAU	Business-as-usual
BAU-ex	BAU PCE-new scenario taking into account the external costs
CRSCA	Coarse recycled siliceous concrete aggregate
CDW	Construction and demolition waste
DGR	Dry Grinding & Refining system
EC	European Commission
EER	Energy efficiency ratio
EoL	End-of-life
EPS	Expanded polystyrene
EU	European Union
EU ETS	European Union Emissions Trading System
FRSCA	Fine recycled siliceous concrete aggregate
FWW	Mineral fiber wool waste
GW	Glass waste
HAS	Heating air classification system
LCA	Life cycle assessment
LCC	Life cycle costing
LCCs	Life cycle costs
PCE-new	Prefabricated concrete element for new building
RCA	Recycled concrete aggregate
URSCA	Ultrafine recycled siliceous concrete aggregate
RGUA	Recycled glass ultrafine admixture
RFUA	Recycled fiber wool ultrafine admixture
SEER	Seasonal energy efficiency ratio
SETAC	Society of Environmental Toxicology and Chemistry
VEEP	European Union Horizon 2020 project VEEP
VEEP-ex	Green PCE-new scenario taking into account the external costs

3.1 Introduction

There is a wide agreement that future economic growth must be driven by greater energy efficiency. The European Union (EU)'s current housing stock is thermally poor, and national energy performance standards are relatively weak when benchmarked against international best practices. Buildings are responsible for approximately 40% of energy use and 36% of CO_2 emissions in the EU (EC 2010). Currently, about 35% of the EU's buildings are over 50 years old and almost 75% of the building stock is energy-inefficient, while the yearly renovation rate is only 0.4–1.2%, depending on the country (EC 2010). The European building industry needs new technologies, products and materials to minimize that energy dependence. More renovation of buildings can lead to significant energy savings, potentially reducing the EU’s total energy use by 5 to 6% and lowering CO_2 emissions by about 5% (EC 2018). One of the key strategies for cutting the energy use of buildings through energy renovation is scaling up the use of novel technologies for highly efficient thermal insulation of a building’s envelope (Morrissey and Horne 2011).

At the same time, one of the largest solid waste streams is construction and demolition waste (CDW). The European Commission (EC) has identified CDW as a priority stream because of the large amounts that are generated and their high potential for reuse and recycling (EC 2011a). In 2005, the EU-27 member states generated approximately 461 Mt of CDW, and the generation volume is expected to reach 520 Mt in 2020 (excavated material excluded) (EC 2011a). Therefore, by 2020, the Waste Framework Directive (2008/98/EC) requires EU member states to take any necessary measures to prepare a minimum of 70% of CDW (by weight) for reuse, recycling and other material recovery, including the use of non-hazardous CDW for backfilling (EC 2008b).

The Netherlands has noticeable performance over CDW management. Nearly 98% of the CDW generated in the Netherlands can be recycled, which is more than in the other member states (EC 2012a). End-of-life (EoL) concrete represents 40% of CDW in the Netherlands, and 100% of this stream is recycled, with more than 97% of it being used in road construction as road base material (Hu et al. 2012). While road construction is expected to remain stable, there is a need for shifting from traditional recycling approaches to novel recycling and recovery solutions. In particular, the fine fraction (0-4 mm), which constitutes roughly 40% of the recycled concrete, is often down-cycled because its incorporation into new concrete still faces technical barriers (Lotfi et al. 2015). Also, some minor (e.g. glass) and emerging (e.g. mineral wool) CDW streams, currently accounting for about 0.7% of the total CDW generation, are expected to grow until 2030 as a consequence of the European regulations on building energy efficiency and building retrofitting (EC 2014b). In global terms, no technological and business solutions have yet been found for recycling those emerging CDW streams, which so far are mostly landfilled. Thus, more advanced and appropriate solutions should be developed to ensure the effective and efficient use of natural resources and to mitigate the associated environmental and economic impacts.

More and more businesses in the construction sector, as well as governments and even consumers are seeking eco-products that are not only financially viable but also bring in environmental, and even social benefits (Zhang et al. 2019b). Also, new products need to meet upcoming challenges concerning climate change and lower carbon footprints, resource depletion and shortages increasing restrictions on the use of toxic substances, lower embodied energy, and best positioning in competitive markets. Over the last few years, novel technologies have been developed aiming to guarantee high-quality recycled raw material for use in new construction products, thereby closing the loops in the manufacturing of concrete and insulation material. In Europe, an innovative and integrated technological system was designed and developed in a VEEP project for the massive retrofitting of the built environment, aiming at cost-effectively recycling CDW and reducing building energy use. VEEP's core technologies include advanced drying recovery (ADR), heating air classification system (HAS) and Dry Grinding & Refining (DGR), which provide the scientific-technological basis for new green concrete recipes containing high levels of upgraded CDW recycled materials. With VEEP, CDW will contribute at least 75% of the total weight of the new concrete, and at least 10% of cement will be replaced by recycled supplementary cementitious CDW materials. VEEP also allows for higher resource efficiency in the novel multilayer precast concrete elements for new building envelopes (PCE-new), through the combination of concrete and superinsulation material manufactured by using recycled CDW materials as raw materials.

Given the need for eco-efficient thermal insulation materials for renovating a building's envelope, it is of great significance to explore the environmental impact and cost-effectiveness of green PCE-new as the building fa çade. Hence the main research question of the present study was "Is the use of concrete façade elements containing secondary materials more economic and environmentally advantageous than the use of elements that are only made of primary material?". This study aimed to answer this question by comparing the economic costs and GHG emissions of two types of PCE-news, one of which is made of both virgin and secondary raw material from the VEEP technological recycling system, the other being a conventional PCE-new with only virgin material. The comparison was based on an integrated life cycle assessment (LCA) conforming to ISO 14040 (2006) and ISO 14044 (2006) and life cycle costing (LCC) based on the SETAC's definition (Swarr et al. 2011; Hunkeler et al. 2008). This study built upon the LCA-LCC analysis framework proposed in Zhang et al. (2019) and explored the potential to harmonize LCA and LCC from stakeholders' perspectives by internalizing the foreseeable environmental costs – carbon emission costs, and on the factor of time by considering "discounting" effects. Through a comparative life cycle assessment of PCE-new panels, this study provides a Dutch case for global issues with respect to CDW generation, GHG emission and energy efficiency in the construction domain. As the evaluation includes a use phase of 120 years it provides an excellent opportunity to investigate the effects of "discounting" on the harmonization of LCA and LCC methods in a combined study.

3.2 Methods

3.2.1 Goal and scope definition

Goal

The goal of this study was to determine the financial effects and carbon mitigation of manufacturing and using the innovative green PCE-new as fa çade for a new building in comparison to those of manufacturing and using conventional PCE-new.

Scope and scenarios

Normally there are five processes in the life cycle of PCE-new: material preparation; manufacturing; installation; in use; disposal. The life cycle that is considered in this study comprises four phases: (I) material preparation, (II) PCE-new manufacturing, (III) PCE-new installation, (IV) PCE-new in use, and (V) PCE-new disposal, as shown in Figure 3.1. Two scenarios are assessed in the study: *VEEP* and *BAU*. In both scenarios, PCE-new will be manufactured to improve the energy efficiency of a building. The differences are that PCE-new from BAU uses virgin material and conventional insulation material. In the VEEP scenario, secondary raw material and the novel insulation material aerogel will be incorporated in PCE-new.

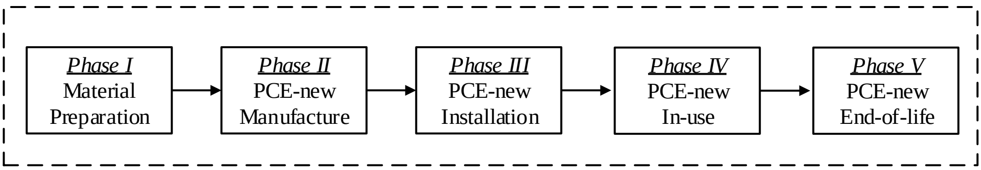

Figure 3.1 Fives phases of this study for the assessment of the PCE-new

3.2.1 Description of the VEEP system

VEEP ADR and HAS technologies

The combined innovative ADR technology and HAS was developed for the simultaneous cost-effective production of high-quality coarse and fine recycled concrete aggregates from concrete waste for green concrete production and green aerogel production. Siliceous concrete waste will be studied in this study. Given that selective demolition and sorting are common practices in the Netherlands, it is assumed that concrete waste fed into ADR and HAS does not contain residue. In this study, EoL siliceous concrete waste is considered as the target concrete waste for producing coarse recycled siliceous concrete aggregate (CRSCA), fine recycled siliceous concrete aggregate (FRSCA), and ultrafine recycled siliceous concrete aggregate (URSCA). The details of ADR and HAS were described in Chapter 2.

VEEP DGR technology

Evolved VEEP Dry Grinding & Refining Recovery (DGR) technology is currently a stationary recycling facility that can produce secondary raw material: recycled glass ultrafine admixture (RGUA) and recycled fiber ultrafine admixture (RFUA), with an average purity level higher than 90%, from emerging building glass waste (GW) and insulating mineral fiber wool waste (FWW). These waste materials will first be pre-crushed by a mobile hammermill when larger amounts of material are processed. Materials are fed three times through the hammermill to achieve a suitable particle size. The whole process is sealed by a small vacuum in the hammermill feeding opening so that no dust or particles can escape from the process. From the hammermill, the milled material is transported pneumatically through a cyclone separator to the collecting bag. Recycled mineral microfibers and ultrafine cementing particles (particle sizes lower than 200 microns) are obtained from this process in order to hopefully incorporate these silica-rich particles effectively into new concrete formulations and aerogel composites for the subsequent manufacture of panels.

VEEP aerogel production

While the BAU scenario involves the use of the conventional insulating material EPS, the VEEP project includes the development of a green cost-effective aerogel using secondary raw materials from CDW. The production of this aerogel relies on the integration of the following steps: (i) low-cost water-glass-based precursor production by using silica-containing CDW recycled materials such as FRSCA, RGUA or RFUA; (ii) gasification; (iii) higher efficient multi-solvent low-temperature supercritical drying. Aerogels can be manufactured in different forms: monolithic, powder, blankets, granules, etc. In the VEEP project, the chosen strategy for preparing aerogel composites is the employment of fibers during the sol-gel step. These fibers will contribute to the mechanical performance of silica-based aerogel materials, allowing the use of the aerogel in the novel precast concrete elements. However, since the VEEP green aerogel is still under development, the present assessment uses lab-scale data. Additionally, due to concerns about business confidentiality, the details of the data will not be disclosed in this study.

Green PCE-new production

The VEEP green recipe concrete contains secondary material, including CRSCA, FRSCA and URSCA from ADR and HAS, RGUA and RFUA from DGR. green PCE-new will be manufactured using the VEEP concrete and the aerogel EPS, as well as rebar cages and welded nets.

3.2.2 Functional unit

Principally, the same functional unit at the system level will be defined for the LCA and LCC. The average lifetime of residential buildings in the Netherlands is 120 years (Sandberg et al. 2016). The functional unit selected for this study was maintaining the thermal comfortableness of 1 m^2 flooring area of a building with the application of a PCE-new façade and active heating and cooling for 120 years based on reference scenarios. In both scenarios, it is assumed that the required building façade per 1 m^2 of flooring area amounts to 0.55 m^2 of PCE-new.

3.3 Life cycle inventory analysis

The LCA software OpenLCA 1.9 was selected to perform the LCA analysis as an assessment instrument with a database of Ecoinvent 3.4 (Allocation, cut-off by classification). For the LCC study, Microsoft office 2016 Excel was used to investigate the main contributions of costs. The system boundaries of the two scenarios are shown in Figure 3.2.

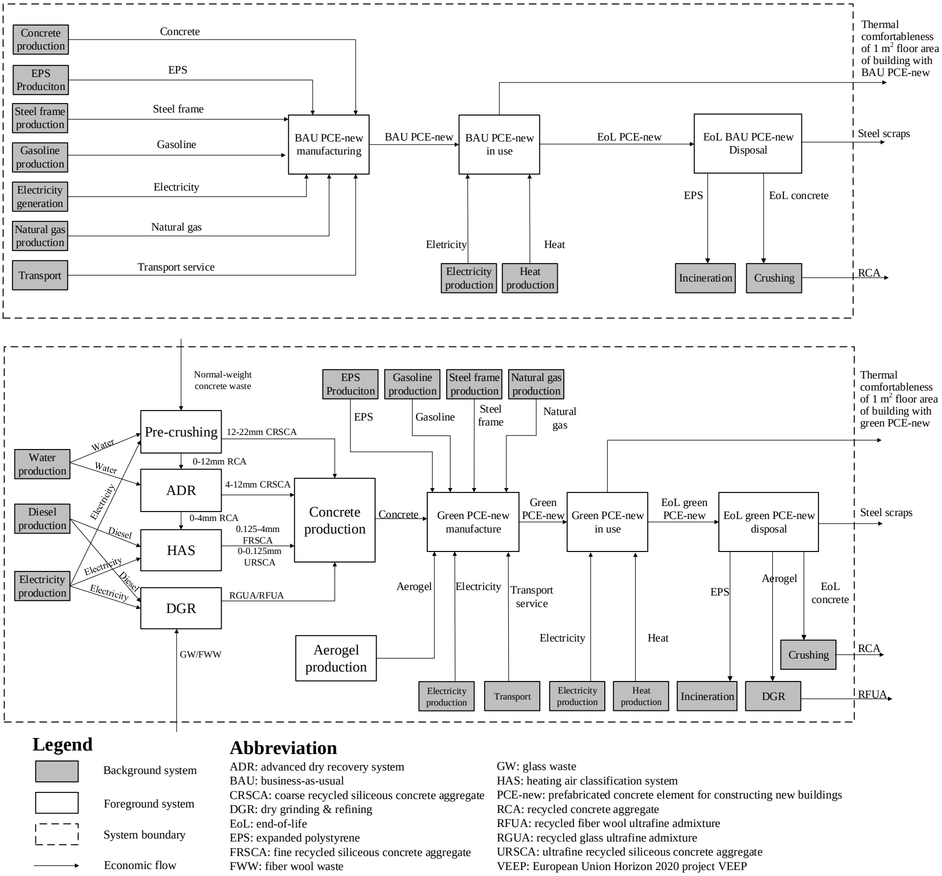

Figure 3.2 System boundaries for the BAU scenario (above) and the VEEP scenario (below)

3.3.1 Environmental inventory

The environmental inventory has been carried out for the BAU and VEEP scenarios and organized into five phases: (I) Material preparation, (II) PCE-new manufacturing, (III) installation, (IV) PCE-new in-use, (V) Disposal of PCE-new as defined in Goal and Scope Definition (Figure 3.1). The details of how the five phases are modeled in shown as follows.

3.3.1.1 Material preparation

In the Material preparation phase, the raw material for manufacturing the green PCE-new will be prepared, including concrete materials (aggregate, cement, additive, etc.), thermal insulation material, rebar cages, and welded nets. In the BAU scenario, only primary raw material was used, while the green PCE-new used both primary and secondary raw material. As the transport of raw material does matter in urban mining (Zhang et al. 2018), the transport costs of virgin material and recycled material are considered.

How the crushing, ADR, HAS are modeled are referred to in previous research (Zhang et al. 2019a). The mass flow diagram of the dry grinding and recovery (DGR) process is shown in Figure 3.3. For the sake of simplicity, it is assumed a 1:1 substitution rate between recycled and virgin materials for GW/FWW.

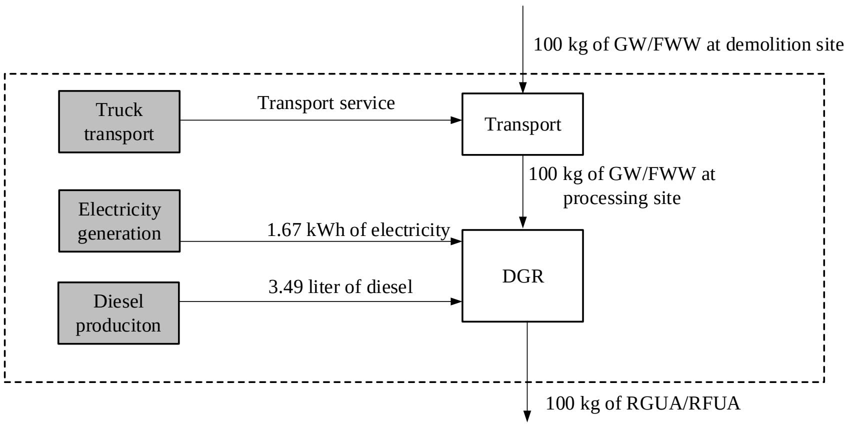

Figure 3.3 Flow diagram of dry grinding & refining (DGR) process. DGR: dry grinding and refining; FWW: fiber wool waste, GW: glass waste; RFUA: recycled fiber wool ultrafine admixture; FGUA: recycled glass ultrafine admixture.

Multifunctional processes in the VEEP scenario include crushing of concrete rubble, ADR, HAS and DGR, which are described in Table 3.1. Allocation is applied to distribute the environmental and economic impacts of functional flow from a multifunctional process. The allocation method for LCC and LCA is process-based allocation. The costs and environmental impact of multifunctional processes are both allocated via the mass of each product.

Table 3.1 Processes with multifunctionality in the VEEP scenario

Process name	Multifunctionality category	Functional flows	Allocation shares	Category
Pre-crushing	Recycling	EoL concrete treatment	50%	Non-target service
		Coarse fraction (0-12mm)	40%	Intermediate product
		Coarse fraction (12-22mm)	10%	Non-target product
ADR	Co-production	CRSCA (4-12mm)	71%	Target product
		Fine fraction (0-4mm)	29%	Intermediate product
HAS	Co-production	FRSCA (0.125-4mm)	80%	Target product
		URSCA (0-0.125mm)	20%	Target product
DGR	Recycling	GW/FWW treatment	50%	Non-target service
		RGUA/RFUA	50%	Target product

Material for the PCE-new and its source is shown in Table A3.1. Lubricating oil for machines is omitted from this study. For the commercially confidential concerns, the exact amounts of the concrete constituents were not shown.

Application of secondary raw material from urban mining in concrete production, especially for on-site recycling, can considerably reduce transportation impact compared to virgin material from conventional mine extraction (Zhang et al. 2018). Besides, Göswein et al. (2018) also proved that transport matters when recycled material is involved. Thus, to make certain if the transport is important when the life cycle of concrete expands, the difference between the transportation of recycled material and virgin material is considered in the material preparation phase. Background process “market for transport, freight, lorry >32 metric ton, EURO3 | transport, freight, lorry >32 metric ton, EURO3 | Cutoff, U - GLO” is selected for the transport simulation. According to the survey at the Delft University of Technology and RINA consulting, it is assumed that truck average travel distance of recycled material is 20 km; the truck travel distance of virgin material is 50 km.

3.3.1.2 PCE-new manufacture

In the PCE-new manufacturing phase, a family of ribbed panels is selected for both scenarios in order to reduce the consumption of concrete, reduce the weight of the panel, and improve the thermal performance of the panel. The cross-section perspective of green PCE-new and BAU PCE-new are shown in Figure 3.4.

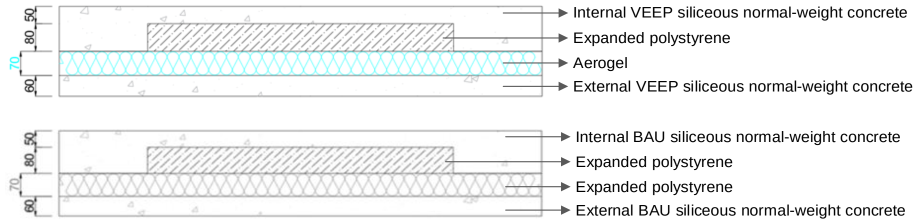

Figure 3.4 Cross-section perspective of green PCE-new (above) and BAU PCE-new (below)

Green PCE-new is a sandwich panel with higher insulation properties due to the material green aerogel and higher contents of secondary raw material from CDW. The BAU PCE-new taken as the reference is also in the form of a sandwich panel with the same stratigraphy but manufactured from traditional concrete (benchmark siliceous concrete produced without the use of secondary raw material) and expandable polystyrene (EPS) as the insulation layer. The sandwich panels will be manufactured with those materials in the material preparation phase in the plant and will then be transported to the construction site.

Both PCE-news have the same structure, thickness, but with different materials. The dimensions of both PCE-news are length 3.6 m; width 2.4 m; thickness 0.26 m. The thickness of concrete layers was designed according to the regulations Eurocode 2, EN 206-1, EN 14992, which requires a minimum of 130 mm for the ribs, 50 mm for the concrete layer between ribs (protected) and 60 mm for the external concrete layer possibly exposed to the environment aggressions. Thermal transmittance measures how effective a material is as an insulator. The thermal transmittance of the green PCE-new is 0.19 W/(m^2 K), then compliant with the project requirements. The thermal transmittance of the BAU PCE-new taken as the reference with EPS as insulation layer (same thickness) is 0.32 W/(m^2 K). It is assumed that all the materials are produced and proceeded in the PCE-new manufacturing plant in the Netherlands. The bill of materials related to the production of one unit of green PCE-new and BAU PCE-new are shown in Table 3.2.

Table 3.2 Component and structure of PCE-new

	Material	Thickness [mm]	Volume [m^3] per unit of PCE	Weight [kg] per unit of PCE
VEEP	VEEP Concrete	60	1.19	2485.46
	Green Aerogel	70	0.61	42.35
	EPS	80	0.45	13.5
	Rebar Cages & welded nets	50	/	117.10
BAU	Concrete	60	1.19	2485.46
	EPS	150	1.05	31.65

Rebar Cages & welded nets	50	/	117.10

Energy usage related to green PCE-new and BAU PCE-new manufacturing is presented in Table A3.2.

3.3.1.3 PCE-new installation

After fabrication, the PCE-new is transported to the construction site for installation. Compared to BAU PCE-new, a dismantlable connecting and anchoring system is applied to conveniently install green PCE-new. Since 90% of the expense on installation is the cost of labor, the dismantlable connecting and anchoring system can also enable a reduction of labor costs through quick installation. It is assumed 30% of the installation cost can be saved by the system. Transport of the PCE-new was assumed 50 km. The input for installation of the BAU and green PCE-new is shown in Table A3.3.

3.3.1.4 PCE-new in-use

In the PCE-new in-use phase, dynamic thermal simulation (DTS) was performed to compare the thermal performances of the two concrete façade elements. The selected case study building was a typical residential building in the capital of the Netherlands, Amsterdam (52°22'N, 4°54'E). The life span of the prefabricated building is assumed to be 120 years. For the climate zone of Amsterdam, the cooling need is rather low. However, to reflect the entire thermal performance of the application of the two PCE-news, this study did take the cooling need into account along with the heating need. DTS at building scale were carried out on a virtual residential multi-story building.

Software DesignBuilder and EnergyPlus were used for dynamic thermal simulations. Figure 3.5 presents the virtual building for the case study. DTS at building scale were carried out on a virtual residential multi-story building. This building is composed of 4 floors for a total floor area equal to 1767 m². The gross floor area of PCE1 used for the façade is equal to 967 m², of which 234 m² for the first floor, 253 m² for the second floor, 253 m² for the third floor, and 227 m² for the top floor. The gross area of PCE-new used for façade is equal to 967 m². Thus, per building floor area needs 0.55 m² of PCE-new.

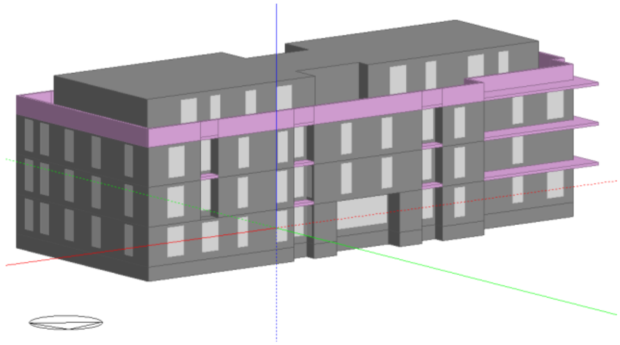

Figure 3.5 Reference virtual building for the case study

Designed thermal conductivity and Thickness of materials in PCE-new of properties used for all DTS are presented in the following Table A3.4 and Table A3.5. According to EN ISO 6946 (2017), no correction (on thermal transmittance) must be applied if the thermal conductivity of the connection, or a part of it, is lower than 1 W/(m·K). For the CHRYSO Flexo connector of PCE-new is made of material with low thermal conductivity (λ<0.231 W/(m·K)), no correction on thermal transmittance was taken into account. For the aerogel, a conservative thermal conductivity value is considered. This value is obtained for a temperature equal to 40 ℃ and for a relative humidity equal to 90%. For these calculations, superficial thermal resistances are not considered. The thermal transmittances of the envelope elements of the building are presented in Table A3.6. The thermal transmittance of selected PCE-new solutions is calculated according to the standard EN ISO 6946 (2017). The heating and cooling scenarios considered are presented in the following Table 3.3.

Table 3.3 Heating and cooling reference Scenarios

	Heating	Cooling	Application
Temperature in occupation	21 ℃	26 ℃	Monday, Tuesday, Thursday, Friday: 00:00 to 10:00 and 18:00 to 24:00 Wednesday: 00:00 to 10:00 and 13:00 to 24:00 Saturday, Sunday: 00:00 to 24:00
Temperature in vacancy	18 ℃	30 ℃	Monday, Tuesday, Thursday, Friday: 10:00 to 18:00 Wednesday: 10:00 to 13:00

According to the dynamic thermal simulation in terms of need heating and cooling referred to the climate of Amsterdam is presented in Table 3.4.

Table 3.4 Need heating and cooling with BAU and green PCE-new in façade

	BAU PCE-new kWh/(m²year)	Green PCE-new kWh/(m²year)
Heating need	29.25	25.90
Cooling need	3.35	3.84

It was assumed that the heating of the building was performed with a boiler of installed power that generates the thermal energy by combustion of natural gas. The background process in Ecoinvent 3.4 "heat production, natural gas, at boiler modulating >100kW | heat, district or industrial, natural gas | Europe without Switzerland" is used for heating need calculation. Concerning cooling, it was assumed that the cold air is produced by an air conditioner using electrical power. According to norm DIN V 18599 (DIN 2011) electricity demand of the air conditioning can be calculated using the following Eq. (1):

$$Electricity\ demand = E_{coldness} / (EER \times f) \tag{1}$$

where $E_{coldness}$ is usable energy for cooling needs (in kWh); *EER* is energy efficiency ratio; *f* is average part load factor. Multiplication of the *EER* with the average part load factor gives the annual seasonal energy efficiency ratio (SEER). According to norm DIN V 18599 (DIN 2011) for split air conditioning (>12kW), the SEER is around 4.7, this means that with 1 kWh of electricity 4.7 kWh of cooling is produced. According to the assumptions above, calculated the Nm^3 of natural gas for heating and the electrical kWh for cooling are shown in Table 3.5. Background process "market for electricity, low voltage | electricity, low voltage | Netherlands" is applied for cooling need calculation.

Table 3.5 electrical energy for the cooling need

	BAU PCE-new	green PCE-new
Electricity [kWh/(m^2·annum)]	0.71	0.82

3.3.1.5 Disposal of PCE-new

When the target building enters its EoL stage, the building will be demolished, and the PCE-news will be deconstructed from the building in structurally intact condition and will be further dismantled manually in situ. A novel anchoring and connection system was applied to the green PCE-new. Dismountable internal epoxy connectors were set between concrete layers, which enable the PCE-new itself as well as the constituents inside the PCE-new to be disassembled more easily. Due to a lack of data, the impact of dismantling the PCE-new from the building and disassembling the PCE-new is currently not considered. Steel, concrete and insulation materials were separated from each other.

Given the high prices for metals, they appear to be in an almost closed-loop (Koutamanis et al. 2018). Metals are collected from the CDW and further re-melted in furnaces to produce new iron and steel. In the disposal phase, steel treatment is processed by collecting and selling it directly on-site. The environmental impact of the follow-up re-melting process will not be considered in the study.

EoL concrete is recycled by crushing on-site with a crusher. The crushing process referred to the previous study (Zhang et al. 2019a). The Allocation method for crushing in the EoL phase of the VEEP scenario is presented in Table A3.7.

For insulations, disposal options for fibrous materials include landfill or incineration (Karatum et al. 2018). EPS and aerogel are both recyclable. The detailed data for EPS recycling is unavailable. It was assumed that EPS is disposed of through incineration. The incineration of the EPS referred to the process "market for waste expanded polystyrene | waste expanded polystyrene | Cutoff, U – GLO". The aerogel was assumed recycled via the DGR.

3.3.2 Economic inventory

To align with the environmental analysis, the economic inventory has been carried out for the BAU and VEEP scenarios and organized into the same five phases as defined in Goal and Scope Definition (Figure 3.1). While different from the environmental assessment, the economic assessment considers the stakeholders' perspective. It distinguishes the costs with clear cost-bears, being producers' costs or consumers' costs, from those without clear cost-bears, being society's costs. The former is termed internal costs, which can be inventoried by monitoring real transactions. However, internal private costs include transfer payments to governments, such as payment for emission allowances in the European Union Emissions Trading System (EU ETS). The transfer payments are currently not discussed in this study. And the latter is termed as external costs, following the scope defined in environmental LCC (Nakamura and Rebitzer 2008) only the "external costs expected to be internalized", which in this study only the carbon emission costs are inventoried.

3.3.2.1 Internal costs

The economic inventory of the internal costs relies on the physical flows associated with the product system, which are the same as defined in the environmental inventory. The cost structure was broken down in this section based on the four defined phases. The geographic scope of the study is the Netherlands, where the field data of the case study were collected. Relevant cost data were collected and expressed in € (euro). The analysis took the Netherlands as the geographical reference area for the price background, and all cost categories are expressed in €. The cost data and their sources for internal costs calculation are presented in Table A3.8.

3.3.2.2 External costs

The external costs was inventoried for the carbon emissions of the BAU and VEEP systems. In 2003, a scheme of greenhouse gas emission allowances was established under the EU ETS. Larger European firms must deliver carbon allowances equal to their emissions, and it can buy or sell carbon allowances that it needs or does not need. The carbon emission costs rose to its highest level in more than a decade in Europe, surpassing 20 euros a metric ton, and it has been predicted that prices will rise to 35 or 40 euro/metric ton on average from 2019 to 2023, with market rates possibly reaching 50 euros in the winters of 2021 and 2022 (Morison and Hodges 2018). The EU ETS does not affect all companies it covers in the same way because of the differences in their reliance on energy and in their production methods (Leadership 2015). Along with this trend, the external costs related to GHG emission might be directly internalized to relevant actors in the future.

In this study, the CO_2 costs was seen as the "external costs expected to be internalized " which was defined in the environmental LCC (Nakamura and Rebitzer 2008). The data for monetization and their sources for external costs calculation are presented in Table A3.9. Those monetary data derived from the VITO is for studies focusing on the comparison of impacts from different building materials or building lines in western Europe (De Nocker and Debacker 2017).

3.4 Life cycle impact assessment

3.4.1 Environmental impact assessment

Climate change poses a fundamental threat to habitats, species and people's livelihoods (Liu et al. 2017). Recent studies have identified a near-linear relationship between global mean temperature change and cumulative GHG emissions (Friedlingstein et al. 2014). For LCA, this study explores the potential of the green PCE-new for greenhouse gas emission mitigation. Global warming (kg CO_2 eq) from CML-IA version 4.4 issues in January 2015 was selected as the sole impact indicator, thus normalization and weighting scheme were not necessary.

3.4.2 Economic impact assessment

According to the environmental LCC guidebook, there is no need to make an impact assessment for LCC. The LCCs of a product is expressed in monetary units which are already comparable, thus there is no threshold and a lower cost is always better (Swarr et al. 2011). However, for a better interpretation of the economic results, (Zhang et al. 2019a) proposed adding an economic impact assessment step in the LCC analysis, which intends to answer three questions: (i) how will the life cycle cost be categorized? (ii) how will the moment of incurring costs and benefits in time be considered? (iii) how will the value of the final cost be expressed? In this study, the economic impact assessment has been implemented according to (Zhang et al. 2019a). While answering these questions, this study intended to explore the potential of sensibly using “external costs” to harmonize LCA and LCC from stakeholders’ perspectives, and the factor of time by investigating the effects of discounting.

Cost breakdown structure

Firstly, the costs are categorized according to the life cycle stages of the PCE-new, thus, the LCCs are estimated as in Eq. (2):

$$LCCs = C_I + C_{II} + C_{III} + C_{IV} + E \quad (2)$$

Where LCCs is life cycle costs; C_I is internal costs incurred in the material preparation phase; C_{II} is internal costs incurred in PCE-new the manufacturing phase; C_{III} is internal costs from PCE-new in the in-use phase; C_{IV} is internal costs from PCE-new in the EoL phase. *E* is the external costs related to GHG emission. The external costs of carbon emission was added to the LCCs to demonstrate to what extent it would affect the economic viability.

Discounting scheme

Whether a study should use a discount rate and if so, which rate, is highly dependent on the study’s defined goal and scope. However, according to the LCC guide book *Environmental Life Cycle Cost* published by SETAC (Hunkeler et al. 2003), environmental LCC usually is a steady-state method, as is the complementary LCA, and discounting the final result of environmental LCC specification is not consistent nor easily carried out and is therefore not recommended. However, in this study, the life span of the prefabricated building is assumed to be 120 years, and therefore the discount rate has to be considered even though it may not be consistent.

Internal costs discounting

Regarding the internal costs, the private discount rate is used for heating and cooling costs, and EoL costs. The costs in the material preparation phase and the PCE-new manufacturing phase will not be discounted, nor will the GHG emission costs. Islam et al. (2015) reviewed building-related LCC studies with consideration of the time value of money and found that discount rates ranged from 2% to 8% worldwide, and from 2.5% to 4% in Europe. Moore and Morrissey (2014) found that the discount rate was usually significantly lower in developed countries. With respect to the time factor on costs, the private discount rate was considered to modify costs incurred in different life cycle stages. The historical time series interest rate in the Netherlands and the Euro area are depicted in Figure 3.6. It can be seen that the interest rate in the Netherlands as well as in the Euro area presents a descending trend and arrives around 0% in 2020. The private discount rate of November 2020 was set as -0.52% for this Dutch case study, while a range of (-1%, 3%) is considered for uncertainty analysis.

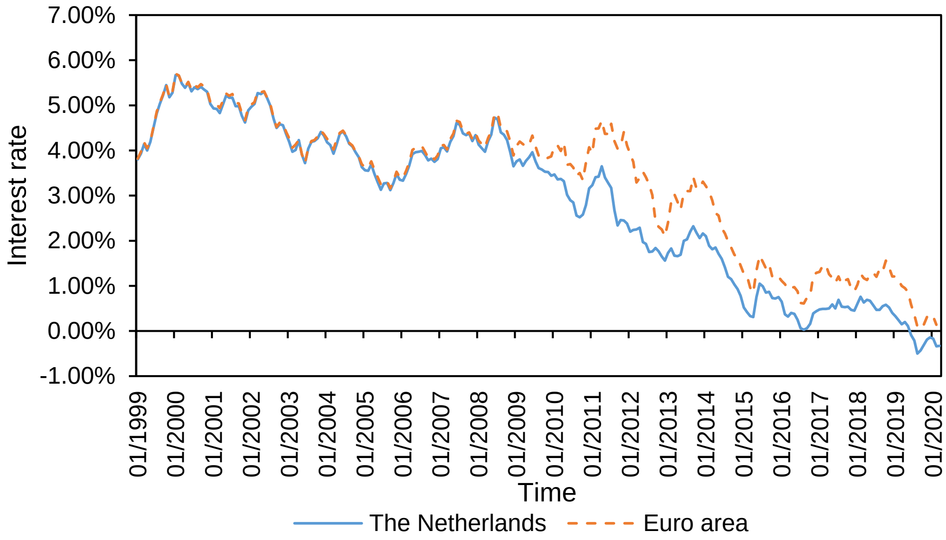

Figure 3.6 Time series interest rate in the Netherlands and Euro area, data from De Nederlandsche Bank (2020).

External costs discounting

As for external costs, a social discount rate was used. Applying discount rates to actualize external costs is a long-stand controversial issue (Weitzman 2011; Arrow et al. 2014; Portney and Weyant 2013). However, this study does not aim to solve the social discounting dilemma once for all but tries to present an example of integrating externality into private costs accounting.

Under the context of the EU ETS, the carbon costs are more likely to be regarded as "real cash flows" in the near future. For the consistency of externality calculation, the associated discount rate of 3% was suggested (De Nocker and Debacker 2017). Weitzman (1998) stated the ''lowest possible'' interest rate should be used for discounting the far-distant future part of any investment project, as Hunkeler et al. (2008) suggested to use the 0.001% rate for discounting of the externalities for an environmental LCC. Tol (2008) found the uncertainty on the social cost of carbon is incredibly large. Even though using unacceptably low discount rates, that the fat tail effect may dominate the conclusions (Weitzman 2011). Thus we used a relatively low discount rate of 0.01% for climate change impact as suggested by (Hunkeler et al. 2008).

The financial result will be expressed as a net present value (NPV) in Euro. The costs incurred at the material preparation stage, at PCE-new manufacturing stage, at the disposal stage was regarded as NPV directly, whereas the costs incurred at the in-use stage was regarded as annual values (A), and costs incurred at the disposal stage regarded as final values (F), which were transferred into NPV according to Eqs. (3) and (4).

$$NPV = A[\frac{1}{i} - \frac{1}{i(1+i)^n}] \tag{3}$$

$$NPV = F\frac{1}{(1+i)^n} \tag{4}$$

Where A is annual energy costs; F is final EoL costs; *i* is (private/social) discount rate; n is building Life span, 120 years. For LCA, discounting of environmental impacts is seldom performed.

3.5 Results

The primary results of the LCA and LCC analysis are presented separately along with the contribution analysis, followed by a sensitivity analysis and uncertainty analysis.

3.5.1 Contribution and comparison analysis

Life cycle greenhouse gas emission

The Life cycle environmental impacts of the 120-year life cycle of the green PCE-new and BAU PCE-new are summarized in Figure 3.7. Generally, the BAU scenario and the VEEP scenario have similar distributions of life cycle GHG emissions. In both scenarios, around 88% and 83% of the life cycle GHG emission is consequent from the operation of the building in the in-use phase. Due to the climate zone of Amsterdam, the cooling need is negligible in both scenarios. The Energy demand for heating accounts for over 90% of operation emissions.

The VEEP system does not show an obvious advantage over the BAU scenario on GHG mitigation. The life cycle GHG emission of the VEEP scenario is only 4.06% lower than that of the BAU scenario. Besides, even using secondary raw materials the VEEP scenario emits more GHG than the BAU scenario. This is because the production of aerogel is a carbon-intensive activity, over 68% of the emission in the material preparation phase is original from aerogel production.

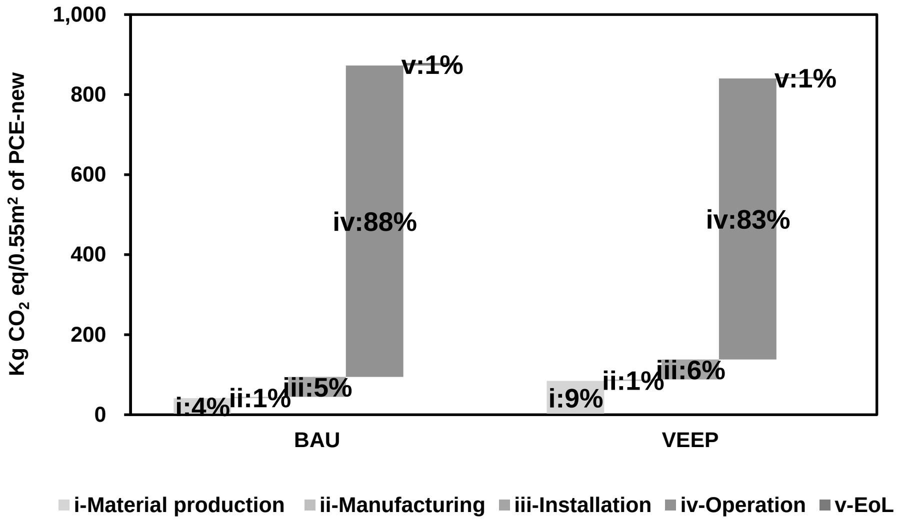

Figure 3.7 Life cycle GHG emission of BAU PCE-new (left) and green PCE-new (right). Note: EPS represents Expandable polystyrene; BAU represents Business-as-usual PCE-new technological scenario; VEEP represents VEEP technological PCE-new scenario; EoL represents end-of-life.

Life cycle costs

The LCC results on the 120-year life cycle of the green PCE-new and the BAU PCE-new are summarized in Figure 3.8. The LCCs of the two scenarios in the figure include internal costs incurred in five life cycle stages and external CO_2 costs. There is an obvious mismatch of the contribution of the installation phase in LCCs and life cycle emission. The emission of the installation phase only accounts for 5–6% in life cycle carbon emission, however, making up 45%–49% in cycle costs. This is because more than 90% of the installation costs are personnel costs, whilst using labor does not generate GHG.

The green PCE-new and BAU PCE-new have a similar distribution of LCCs. The LCCs of the BAU PCE-new is 501.63 €/0.55m^2. The costs incurred in the installation phase (49%) and the in-use phase (44%) together account for more than 90% of the LCCs. For the VEEP scenario, the LCCs of green PCE-new is about 483.66 €/0.55m^2. The costs of the installation phase and in-use phase account for 87% of the LCCs. The green PCE-new does not present a noticeably economic advantage over the BAU scenario. The LCCs of the green PCE-new is 3.58% lower than that of the BAU PCE-new. Even though considering carbon costs, the cost reduction just increases by 4.04%.

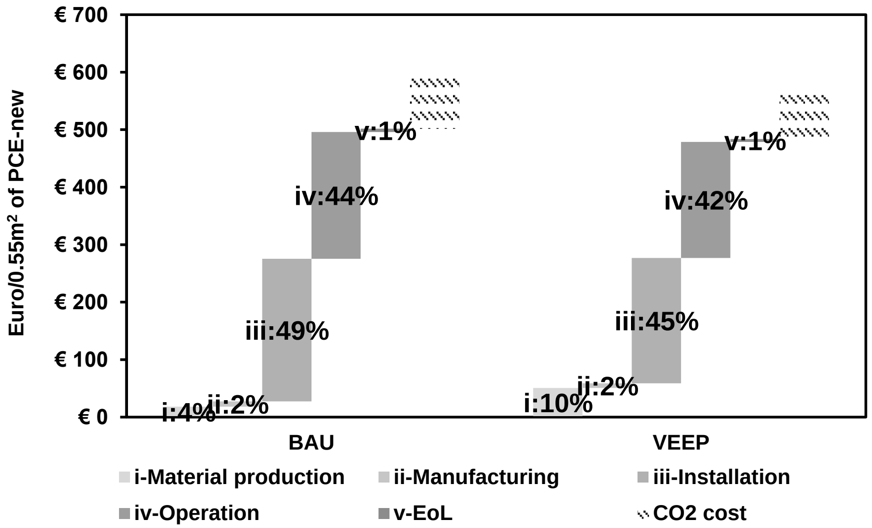

Figure 3.8 Life cycle costs of BAU PCE-new and green PCE-new. Note: Note: EPS represents Expandable polystyrene; BAU represents Business-as-usual PCE-new technological scenario; VEEP represents VEEP technological PCE-new scenario; EoL represents End-of-life.

3.5.2 Sensitivity analysis

To better understand how the CO_2 costs would affect the LCC results in reality, we assumed scenarios in which CO_2 costs are directly borne by relevant actors and are seen as internal costs in the LCCs. In this case, the discount rate is applied to the CO_2 costs that were allocated to each phase accordingly. We established two new scenarios, BAU-ex and VEEP-ex, which do consider the CO_2 costs. Cumulative cost curves of the four scenarios are projected in Figure 3.9. If CO_2 costs are considered, the cost reduction performance of VEEP-ex (compared to BAU-ex) is slightly better than VEEP (compared to BAU).

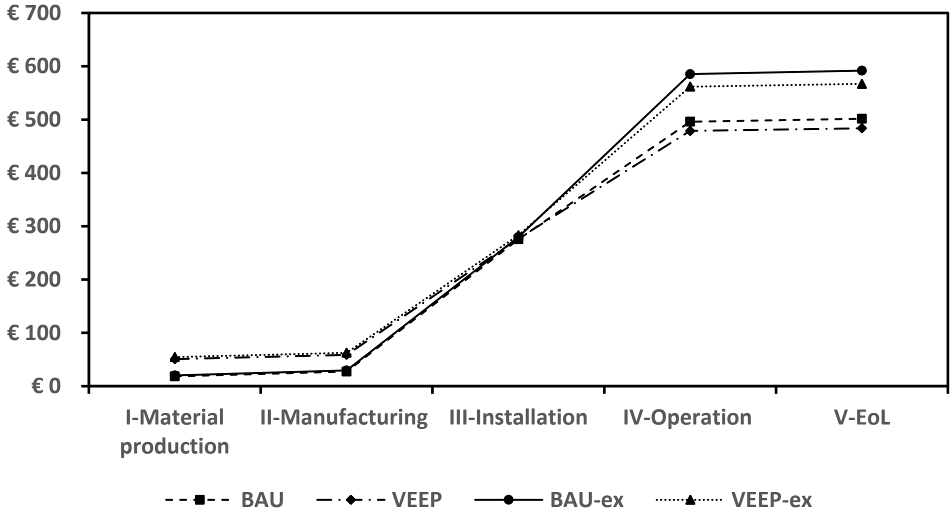

Figure 3.9 Cumulative life cycle costs of four scenarios: BAU, VEEP, BAU-ex, VEEP-ex. Note: Note: EPS represents Expandable polystyrene; BAU represents Business-as-usual PCE-new technological scenario; VEEP represents VEEP technological PCE-new scenario; BAU-ex represents BAU PCE-new scenario taking into account the external costs; VEEP-ex represents green PCE-new scenario taking into account the external costs; EoL represents end-of-life.

The robustness of these scenarios was first verified using a sensitivity analysis. As explained in the contribution analysis, 9 factors related to heating, installation, the aerogel production are considered in the sensitivity analysis as listed in Table 3.6 were considered.

Table 3.6 Factors for robustness analysis. Note: (a) as mentioned in Section 3.3.2.2; (b) for those LCI data that do not have a source of uncertainty range, a single standard error range of ±5% for the LCI data was selected in this study, which is seen as an accepted assumption regarding the uncertainty of LCI data (Huijbregts et al. 2003); (c) data from a survey to the Keey Aerogel in March 2020; (d) data from a survey to the Nobatek in March 2020; (e) from literature (De Nocker and Debacker 2017).

Code	Factors	Value	Range of uncertainty
f_1	Private discount rate	-0.52%	(-1%,3%) [a]
f_2	Social discount rate	0.01%	(-1%,3%) [a]
f_3	Heating price [€/kWh]	0.04	0.04 ± 5% [b]
f_4	Aerogel cost [€/0.01m^3]	10.00	(8.00,12.00) [c]
f_5	Reduction of labor cost in installation phase	30%	(10%, 50%) [d]
f_6	CO_2 monetary indicator for construction phase [€/kg CO_2 eq]	0.045	(0.023,0.09) [e]
f_7	CO_2 monetary indicator for in-use phase [€/kg CO_2 eq]	0.11	(0.055,0.22)[e]

f_8	CO_2 monetary indicator for EoL phase [€/kg CO_2 eq]	0.14	(0.070,0.280) [e]
f_9	BAU/VEEP heating demand [kWh/(m²year)]	29.25/25.90	29.25 ± 5%/25.90 ± 5% [b]

The sensitivity analysis was conducted to identify the sensitivity of the 9 factors by decreasing 10% of each factor. The results are depicted in a radar plot in Figure 3.10. All scenarios are sensitive to heating related factors such as heating price and annual heating demand. Scenarios including external costs are more sensitive to heating demand while scenarios only containing internal costs are more sensitive to the heating price. Furthermore, four scenarios are relatively sensitive to the market interest rate but insensitive to the social discount rate. Besides, the VEEP and VEEP-ex scenarios are also sensitive to the reduction rate of labor cost in the installation phase.

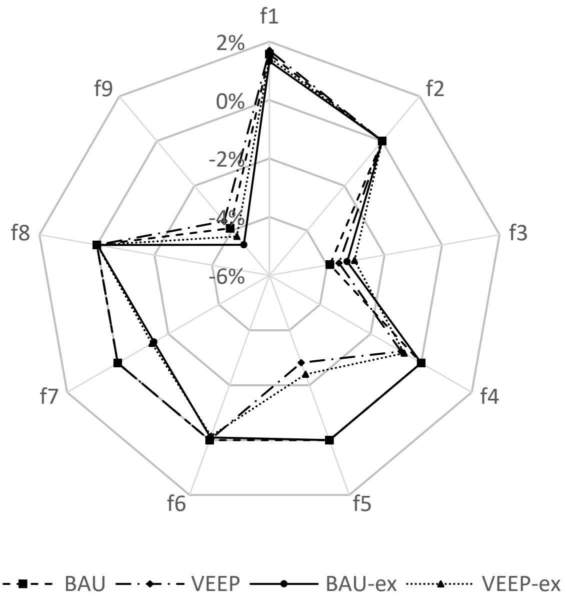

Figure 3.10 Sensitivity analysis of relevant factors in the BAU and VEEP scenarios (each factor decreased by 10%). Note: BAU represents Business-as-usual PCE-new scenario; VEEP represents green PCE-new scenario; BAU-ex represents BAU PCE-new scenario taking into account the external costs; VEEP-ex represents green PCE-new scenario taking into account the external costs.

3.5.3 Uncertainty analysis

The factors which were evaluated in the sensitivity analysis were also selected for the uncertainty analysis. The value ranges of those factors are determined by a variety of sources, as shown in Table 3.6. Values of those factors were assumed a uniform distribution varying from minimum to maximum value. To what extent the volatility of the factors affecting the LCCs is shown in Figure 3.11. Generally, scenarios that accounted for externality, BAU-ex and VEEP-ex, have a wider range of uncertainty which is mainly originated from the external discount rate and the monetary indicator for the in-use phase. For all four scenarios, the largest uncertainty stems from the fluctuation of the internal discount rate. Since the EoL costs of the four scenarios are negligible, the uncertainty of monetary indicators for the EoL phase barely affects the LCCs.

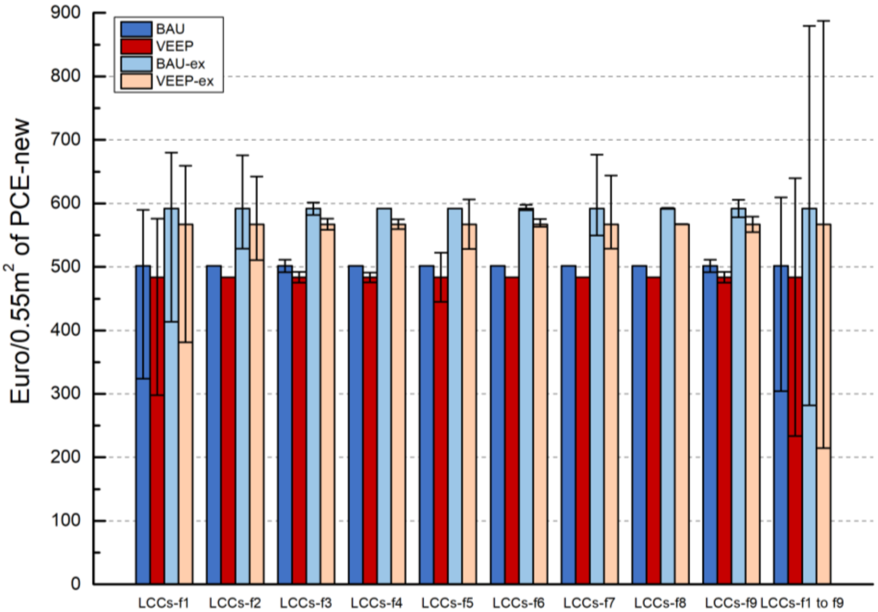

Figure 3.11 Uncertainty analysis of the LCCs: cohort LCCs-f1 to LCCs-f9 present the extent to which the fluctuation of the factors affects the uncertainty of the LCCs respectively; cohort LCCs-f1 to f9 show the summarized uncertainty of LCCs when considering all factors. Note: BAU represents Business-as-usual PCE-new technological scenario; VEEP represents VEEP technological PCE-new scenario; BAU-ex represents BAU PCE-new scenario taking into account the external costs; VEEP-ex represents green PCE-new scenario taking into account the external costs; LCCs represents Life cycle costs.

3.6 Discussion

Previous studies (Islam et al. 2014; Dong et al. 2005; Wan Omar et al. 2014; Dissanayake et al. 2017; Ottelé et al. 2011) assessed the economic and environmental performance of wall assemblage in buildings. However, it is impossible to validate the outcomes of this particular case study by comparing it to other studies, because LCA and LCC studies of residential building facades vary considerably in terms of functional units, assumptions, database, wholesale price index, and system boundaries. Additionally, they vary in building typology and life span, local climate, and inclusion or exclusion of maintenance. Results from the analysis of contribution, sensitivity and uncertainty are further discussed in this section.

At a certain degree of uncertainty, the green PCE-new system only shows slightly better economic and environmental performance in comparison with the BAU PCE-new. A few points that were not considered in the robustness analysis need to be mentioned. **First**, in the VEEP system, the production costs and environmental impacts of the secondary raw materials recovered from CDW was estimated using a mass-based allocation method. The prices used in the case study reflect only the Dutch market situation under current environmental regulations and resource conservation policies. Applying VEEP technologies in other regions with different market and policy situations may amplify or worsen the potential economic advantages of VEEP scenarios. **Second**, since green aerogel is under development. It is not financially viable yet, nor did it apparently improve the thermal performance of the green PCE-new compared to EPS. However, as a promising insulating material aerogel is crucial to the ongoing building energy renovation. This study assumed a conservative thermal conductivity value of 0.0157 W/(m·K) for the green aerogel. However, the target thermal conductivity of the green aerogel is equal to 0.012 W/(m·K). If this requirement is satisfied, the U value of green PCE-new will be below 0.17 W/(m^2·K). Besides, the production of green aerogel is currently carbon-intensive. In the EoL phase, this study assumed that aerogel was recycled by the DGR. Whereas the aerogel blankets have the potential to be fully reused, which can avoid a large amount of GHG emission from the new aerogel production. **Third**, including external CO_2 costs in LCC increases the financial advantages of low-carbon options, even though the promotion of economic viability by including externality is not significant. This indicates a government could use policy tools to propagate the use of low-carbon products by raising environmental taxes or emission fees. **Finally**, while previous research found that the LCC approach is sensitive to changes in discount rates (Islam et al. 2015), which is in accordance with the findings of this study. A high discount rate can take the edge off the economic advantages of the VEEP system in the in-use phase, flipping the evaluating results from country to country.

3.7 Conclusions

This paper presents an integrated environmental LCC and LCA study exploring to which extent the LCCs and environmental impact of building envelopes can be reduced by applying a green PCE-new system containing secondary material as opposed to a BAU PCE-new. LCA was used to estimate the GHG emission during the main life cycle phases of both PCE-news. While LCC was used to examine the systems' financial performance in parallel with LCA. To explore how externality will affect the PCE-new's economic performance, the GHG emission was internalized via monetary indicators, leading to two additional scenarios, BAU-ex and VEEP-ex.

The final results show that the life cycle GHG emission of the VEEP scenario is only 4.06% lower than that of the BAU scenario, and the majority of the carbon mitigation results from the heating energy saving. From the economic perspective, the LCCs of the green PCE-new is also 3.58% lower than that of the BAU scenario. If externality is considered, the difference in LCCs is slightly larger, amounting to 4.04% in favor of the green PCE-new, but this also leads to greater uncertainty. In the VEEP scenario, about 68% and 76% of the life cycle GHG emission and LCCs result from green aerogel production. However, the aerogel does not present an obvious advantage in energy saving for green PCE-new in the in-use phase if assumed a conservative thermal conductivity.

Sensitivity and uncertainty analysis were carried out to understand the robustness of the results. It was found that both BAU and green PCE-new are noticeably sensitive to heating demand. Thus, further work should focus on optimizing the thermal transmittance of the PCE-new. For green PCE-new, the green aerogel was shown to be the main cost stressor and GHG emitter in the material production phase. As it is under development, currently it does not show a noticeable economical advantage over EPS, nor does it show a better thermal performance than EPS. Moreover, the biggest uncertainty of the results from the discount rate is due to its wide range of possibilities.

It is necessary to note some limitations of the study. **First**, to reduce the uncertainty from monetization to some point, GHG emission was selected as the sole environmental impact indicator. However, other impact categories, such as resource depletion can be also significant in CDW management. **Second**, the dynamic thermal simulation was conducted using two different insulating materials in the PCE-news on the condition that both PCE-news maintain the same thickness. However, other potential scenarios could be established to compare the BAU and VEEP scenarios from multiple angles, such as choosing two PCE-news that use the same insulation or PCE-news with the same U value. **Third**, due to the limitations of the OpenLCA software, partial sensitivity and uncertainty analysis were performed. **Last** but not least, the controversial issues of monetization and discounting in an integrated LCC-LCA study have not been elaborated. On the one hand, the discount rate was inconsistently applied to LCC and LCA, and each cost component of LCC. On the other hand, in BAU-ex and VEEP-ex scenarios, the external cost was internalized thus market-related discount rates were applied. But the issue of discount rate for social cost including real externalities is much more complex, which is not discussed in the study.

Nevertheless, this combined LCA and LCC study of the PCE-new case explored the potential to resolve the inconsistency between the two analytical methods, from stakeholders' perspective and the factor of time, by including external costs and discounting. The study shows that to support sensible decision making, a systematic method to standardize the treatment on to be internalized external costs specify the discounting scheme should be developed for the combined use of LCA and LCC. These factors will be examined in our future studies.

Acknowledgements

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Appendix

Table A3.1 Bill of Material related to green PCE-new and BAU PCE-new

The material of the PCE-new		BAU	VEEP
Concrete	Cement (CEM III/A)	Unit process referred: "market for cement, blast furnace slag 36-65% | cement, blast furnace slag 36-65%, non-US | Cutoff, U - Europe without Switzerland"	Unit process referred: "market for cement, blast furnace slag 36-65% | cement, blast furnace slag 36-65%, non-US | Cutoff, U - Europe without Switzerland"
	URSCA	/	From HAS
	RGUA	/	From DGR
	Limestone	Unit process referred: "market for lime, packed | lime, packed | Cutoff, U-RoW"	Unit process referred: "market for lime, packed | lime, packed | Cutoff, U-RoW"
	RFUA	/	From DGR
	Siliceous sand	Unit process referred: "market for silica sand | silica sand | Cutoff, U - GLO"	/
	FRSCA	/	From HAS

The material of the PCE-new		BAU	VEEP
	Siliceous gravel	unit process referred: “market for silica sand | silica sand | Cutoff, U - GLO”	/
	CRSCA	/	From ADR
	Superplasticizer	Unit process referred: “market for plasticiser, for concrete, based on sulfonated melamine formaldehyde | plasticiser, for concrete, based on sulfonated melamine formaldehyde | Cutoff, U - GLO”	Unit process referred: “market for plasticiser, for concrete, based on sulfonated melamine formaldehyde | plasticiser, for concrete, based on sulfonated melamine formaldehyde | Cutoff, U - GLO”
	Water	Unit process referred: “market for tap water | tap water | Cutoff, U - Europe without Switzerland”	Unit process referred: “market for tap water | tap water | Cutoff, U - Europe without Switzerland”
Insulation material	EPS	Unit process referred: “polystyrene foam slab production, 100% recycled | polystyrene foam slab | Cutoff, U - RoW”	Unit process referred: “polystyrene foam slab production, 100% recycled | polystyrene foam slab | Cutoff, U - RoW”
	Aerogel	/	From VEEP aerogel production
Steel frame	Rebar Cages & welded nets	Unit process referred: “reinforcing steel production | reinforcing steel | Europe”	Unit process referred: “reinforcing steel production | reinforcing steel | Europe”

Table A3.2 Energy usage related to green PCE-new and BAU PCE-new manufacturing

Energy carrier	Energy usage per unit of PCE-new	Unit processes referred
Electricity	39.70 kWh	“market for electricity, high voltage | electricity, high voltage | Cutoff, U - NL”
Natural gas	292.41 MJ	“natural gas, burned in gas motor, for storage | natural gas, burned in gas motor, for storage | Cutoff, U - NL”
Diesel	107.06 MJ	“market for diesel, burned in building machine | diesel, burned in building machine | Cutoff, U - GLO”

Table A3.3 Input for installation of the BAU and green PCE-new

Input for per m2 of PCE-new	Amount	Unit processes referred in Ecoinvent 3.4
Transport	307.69 t ·km	“market for transport, freight, lorry 16-32 metric ton, EURO3 | transport, freight, lorry 16-32 metric ton, EURO3 | Cutoff, U – GLO”
Foundation slabs	0.08 m^3	“concrete production 30-32MPa, RNA only | concrete, 30-32MPa | Cutoff, U – RoW”

Steel structure	15.63 kg	"market for sheet rolling, steel | sheet rolling, steel | Cutoff, U – GLO"
Floor slabs	0.03 m^3	"concrete production 30-32MPa, RNA only | concrete, 30-32MPa | Cutoff, U – RoW"
Electricity	7.50 MJ	"market for electricity, high voltage | electricity, high voltage | Cutoff, U – NL"

Table A3.4 Designed thermal conductivity and Thickness of materials in green PCE-new

Material (external layer to internal layer)	Designed thermal conductivity-λ [W/(m. K)]	Thickness [mm]
External concrete	2.080	60
Aerogel	0.0157	70
EPS	0.031	80
Internal concrete	1.900	50

Table A3.5 Designed thermal conductivity and Thickness of materials in BAU PCE-new

Material (external layer to internal layer)	Designed thermal conductivity-λ [W/(m.K)]	Thickness [mm]
External concrete	2.080	60
EPS	0.031	70
EPS	0.031	80
Internal concrete	1.900	50

Table A3.6 Thermal transmittance of the building envelope for dynamic thermal simulation with PCE-news used as façade

Element	Thermal transmittance [W/(m²K)]
Floor	0.181
Roof	0.118
Glazing	1.300
BAU PCE-new	0.320
Green PCE-new	0.190

Table A3.7 Allocation method for crushing in EoL phase of VEEP scenario

Process name	Multifunctionality category	Functional flows	Allocation shares	Category
Crushing	Recycling	EoL concrete treatment	50%	Target service
		RCA	50%	Non-target product

Table A3.8 Internal cost data and sources

Life cycle phase		Cost detail and its sources
Material preparation phase	Siliceous concrete	**Raw material:** Virgin siliceous sand/gravel price is 31.20 €/metric ton, data referred to process “market for silica sand | silica sand | Cutoff, U - GLO” [a]; Virgin cement price is 61.50 €/metric ton, data referred to process “market for cement, blast furnace slag 36-65% | cement, blast furnace slag 36-65%, non-US | Cutoff, U - Europe without Switzerland” [a]; Limestone powder price is 122.00 €/metric ton, data referred to process "market for lime, packed | lime, packed | Cutoff, U - RoW” [a]; Superplasticizer price is 1280 €/metric ton, data referred to process “chemical production, organic | chemical, organic | Cutoff, U – GLO” [a]. **Utilities:** Diesel price is 0.73 €/L, data referred to the process “diesel, burned in building machine | diesel, burned in building machine | Cutoff, U – GLO” [a]; Water (for dust control) price is 0.16 €/L [b]; Non-household electricity price is 0.06 €/kWh [c]. **Personnel:** Wages and salaries in the construction sector are set as 35.9 €/man-hour [d]. **Equipment:** Hourly depreciation of each piece of equipment in this study is as follows: HAS is 14.73 €/h [e]; crushing set is 147.67 €/h [e]; ADR is 83.73 €/h [e]; DGR set 3.18 €/h [f]. **Transport:** transport cost of raw material and waste is 0.1 €/km·t [g] (hereafter).
	Aerogel	The comprehensive unit cost for aerogel is 10.00 €/m^2 (thickness 1cm) [h].
	EPS	EPS price is 1240.00 €/metric ton [a], data referred to process “polystyrene foam slab production, 100% recycled | polystyrene foam slab | Cutoff, U - RoW”.
	Steel frame	Steel frame price is 537.00 €/metric ton [a], data referred to process “reinforcing steel production | reinforcing steel | Cutoff, U-RER”.
PCE-new manufacturing phase	Equipment	Equipment depreciation is for per m^2 of EPS is as follows [i]: 0.80 €/m^2 for BAU PCE-new; 0.70 €/m^2 for green PCE-new.
	Personnel	Personnel cost for per m^2 of PCE-new is as follows [i]: 13.40 €/m^2 for BAU PCE-new; 11.7 €/m^2 for green PCE-new.
	Utilities	Energy cost per m^2 of EPS is as follows [i]:

		Electricity cost is 0.30 €/m² [i]. Natural gas cost is 0.30 €/m² [i]. Gasoline cost is 0.40 €/m² [i].
	Transport	Transport cost per panel is 35.75 €/per panel, 50km of transport distance is assumed [i].
PCE-new installation phase	Foundation slabs	3.99 € per m² of VEEP/BAU PCE-new [i].
	Steel	3.99 € per m² of VEEP/BAU PCE-new [i].
	Floor slabs	1.49 € per m² of VEEP/BAU PCE-new [i].
	Personnel cost	354.17 € per m² of BAU PCE-new; 247.92 per m² of green PCE-new [i].
	Electricity	0.17€ per m² of VEEP/BAU PCE-new [i].
	Transport	4.17 € per m² of VEEP/BAU PCE-new [i].
PCE-new in-use phase	Heating energy	Cost related to air water heat pump. Heating cost is 0.04 €/kWh, referred to the process "market for floor heating from air-water heat pump | heat, air-water heat pump 10kW | Cutoff, U - Europe without Switzerland" [a].
	Cooling energy	Cost related to electricity for household cooling. The electricity price is 0.21 €/kWh [c].
EoL PCE-new disposal	EoL concrete crushing	"Crushing" in the PCE-new disposal phase was modeled as same as the "crushing" process in the material preparation phase which referred to literature (Zhang et al. 2019a).
	EPS incineration	Reception of insulation at waste processor 80.00 €/metric ton excludes transport [b].
	Aerogel recycling	The aerogel is recycled by DGR.
	Steel recycling	Sell of other ferrous metals at demolition site 133.12 €/metric ton [b].

Notes:

[a] Data from database Ecoinvent 3.4 for OpenLCA 1.7.4;

[b] Data from HISER project report D5.4 "Final Report of Integrated environmental and economic assessment for the HISER case studies" via www.hiserproject.eu.

[c] Data from Eurostat "Electricity prices by type of user" (the Netherlands, 2017), via https://ec.europa.eu/eurostat/tgm/table.do?tab=table&init=1&language=en&pcode=ten00117&plugin=1;

[d] Data from Eurostat, Labour cost levels by NACE Rev. 2 activity (the Netherlands, 2018), via http://ec.europa.eu/eurostat/web/products-datasets/-/lc_lci_lev ;

[e] Data from an interview with Dr. Abraham Gebremariam and Dr. Francesco Di Maio from the Technology University of Delft on July 2018;

[f] Data obtained from interviewing with Mr. Ismo Tiihonen on July 2018;

[g] Data investigated via interviewing with Mr. Frank Rens from Strukton BV in November 2018;

[h] Data obtained from VEEP inner report No. D3.3 on May 2019, authorized by Dr. Francisco Ruiz and Dr. Kanda Philippe from Keey Aerogel;

[i] Data from VEEP inner report No. D6.2 on June 2019 from RINA Consulting;

Table A3.9 Monetary values for monetization of global warming

Indicator per phase	Applied to phases in this study	Descriptions
Construction	Material preparation phase, manufacturing phase	Monetary indicator (low/central/high) for global warming of building materials in the construction phase is 0.023/0.045/0.09 €/kg CO_2 eq. The central value 0.045 €/kg CO_2 eq is selected for assessment.
Use phase	In-use phase	Monetary indicator (low/central/high) for global warming of building materials in the use phase is 0.055/0.11/0.22 €/kg CO_2 eq. The central value 0.11 €/kg CO_2 eq is selected for assessment.
End of life	EoL disposal	Monetary indicator (low/central/high) for global warming of building materials in the EoL phase is 0.070/0.140/0.280 €/kg CO_2 eq. The central value 0.140 €/kg CO_2 eq is selected for assessment.