Circular, biomimicry-based, and energy-efficient façade development for renovating terraced dwellings in the Netherlands

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Abstract

Many studies concerning lowering the Operational Energy (OE) of existing dwellings have been conducted. However, those studies barely cover its collateral Embodied Energy (EE). As the Circular Economy is gaining momentum and the balance between OE and EE is shifting, the Life Cycle Energy Performance (LCEP) is becoming increasingly relevant as an indicator. LCEP accounts for all the OE and EE a building consumes during its lifespan. However, clear insights into the LCEP are still to be investigated. This study focuses on developing a circular and energy-efficient renovation solution for a common terraced dwelling typology in the Netherlands. The energy-efficient renovation is based on three circular strategies: Biomimicry, Urban Mining, and Design for Disassembly (DfD), covering the aspects of EE and future reuse of building materials and components. The developed renovation solution reduces 82% of the LCEP compared to the existing scenario. With additional photovoltaic (PV) modules, the dwelling reduces 100% of the LCEP. Applying biomimicry, urban mining, and DfD-based renovation can significantly lower the overall LCEP and its collateral environmental impacts to achieve a Life Cycle Zero Energy circular renovation.

Keywords

Circular Façade Design, Open-joint ventilated façade, Circular Energy Renovation, Biomimicry, Design for Disassembly, Urban Mining, Life Cycle Energy Performance.

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1 INTRODUCTION

Buildings are responsible for up to 40% of Operational Energy (OE) consumption in the European Union (EU) (Poel et al., 2007), and more than 60% of this energy comes out of fossil fuels, with an alarming collateral carbon emission rate (Martins et al., 2018). OE can be defined as the energy required to maintain comfort conditions and the building itself, such as lighting, heating and cooling systems (Li et al., 2020).

Therefore, to lower OE consumption as a path to reduce carbon emissions, policies and developments are underway to achieve a nearly Zero Energy Building (nZEB). An nZEB is a building with high energy performance in which the low amount of energy required is covered by energy generation from renewable sources on-site or nearby, such as photovoltaic (PV) modules (Chesné et al., 2012; European Commission, 2016). By 2021, all new buildings in the EU should be nZEB, and by 2050 the complete building stock should achieve this target (European Commission, 2010).

LIST OF ABBREVIATIONS	
CDW	Construction and Demolition Waste
DfD	Design for Disassembly
EC	European Commission
ECO2	Embodied Carbon
EE	Embodied Energy
EU	European Union
LCEP	Life Cycle Energy Performance
nZEB	nearly Zero Energy Building
OE	Operational Energy
PV	Photovoltaic
ZEB	Zero Energy Building

The façade plays an essential role in OE reduction, as most heat and light transfers occur through it (Tokuç et al., 2018). Therefore, the façade design strategy highly influences the thermal performance of a building. A commonly adopted solution towards an energy-efficient building is the addition of inorganic fibrous materials and organic foamy materials, such as polyurethane and extruded polystyrene insulation throughout the façade (Papadopoulos, 2005). Reused and bio-based insulation materials are less applied, and their full potential and effect on LCEP are still to be thoroughly investigated.

A significant amount of studies has been conducted related to energy-efficient buildings' façades design, such as ventilated façades (Ahmed et al., 2015; Balocco, 2002; De Gracia et al., 2013; Fantucci et al., 2013, 2020; Gratia & De Herde, 2003; Medved et al., 2019; Sanjuan et al., 2011; Zhou & Chen, 2010), showing a decrease of up to 87% of the energy consumption during summer (Rasca, 2014). However, these studies barely cover the energy consumption related to the building's construction, demolition, disposal phases, and raw material consumption, which is covered in this research.

Of all extracted materials, 50% is attributed to buildings (Cottafava et al., 2020), and according to the European Commission (EC), construction waste accounts for over 35% of all waste generated in the EU, with its collateral Embodied Energy (EE) (European Commission, 2020c). The EE is defined as the energy required in buildings and their materials during the manufacturing, construction, final demolition, and disposal phases (Dixit et al., 2010). Hence, the EC set up a long-term circular economy plan: the construction sector will be fully circular by 2050, and the intermediate goal is to have a 50% circular economy by 2030 (European Commission, 2020a).

Due to the growing progress toward a Zero Energy Building (ZEB), the shift between OE and the effect of building materials is becoming increasingly relevant for the environmental impact (BPIE, 2021; Sartori & Hestnes, 2007). It means that with OE reduction, the EE percentage tends to have a higher impact on the total energy consumption during the building's lifespan. Figure 1 visually expresses the balance shift between OE and EE for different energy profiles of dwellings. It shows that the better the energy efficiency of the dwelling (such as passive houses), the bigger the significance of EE. Therefore, the assessment of EE associated with the buildings' materials, and the buildings' energy performance by OE, are becoming equally vital to effectively evaluate the way to a sustainable built environment.

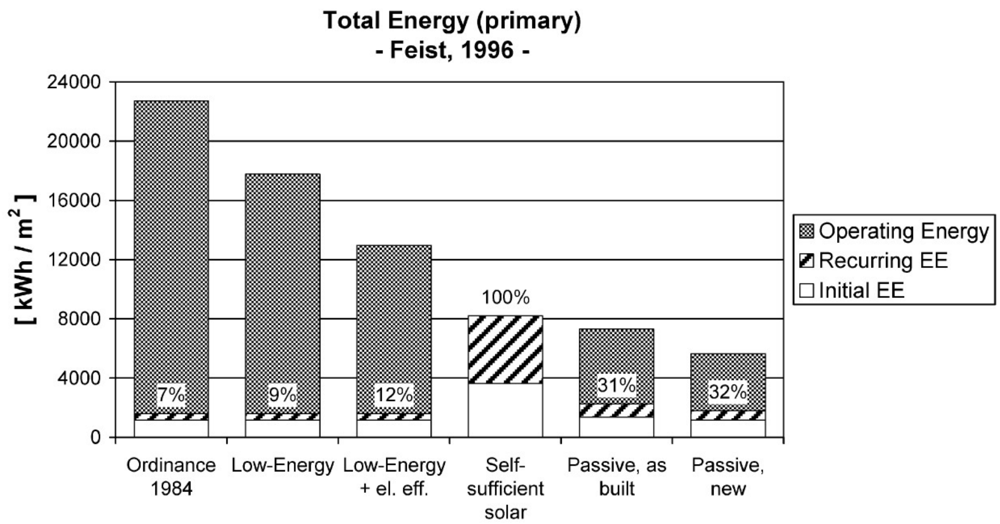


FIG. 1 Life cycle energy demand in different dwelling types (Source: (Feist, 1996))

In order to evaluate OE and EE at the same scale, this paper makes use of the Life Cycle Energy Performance (LCEP) analysis. The LCEP of a building corresponds to the summation of the total OE and EE consumption throughout its lifespan, enabling to address the total energy input and formulate strategies to reduce the primary energy use of the building and control emissions (Ramesh et al., 2010). In this sense, the LCEP should be as low as possible to reach the most sustainable building performance, assessing both EE and OE.

Accordingly to the EC, 85 to 95% of the existing buildings will remain standing by 2050 (European Commission, 2020b). This means that to achieve the mentioned goals, it is necessary to focus on the new buildings as well as on renovating existing ones. In this sense, the Renovation Wave comes as a strategy established by the EC in 2020 to double renovation rates in the next ten years and ensure higher energy and resource efficiency within the EU (European Commission, 2020b).

However, the total LCEP of building renovations has to be investigated as one path of the Renovation Wave to achieve the European plan using circular strategies and energy efficiency improvement. Therefore, this study aims to develop a circular and energy-efficient renovation of a common terraced dwelling type in the Netherlands, aiming at achieving a minimal LCEP, based on three strategies: firstly, "biomimicry" aiming at lowering the OE consumption and improving summer comfort; secondly, "urban mining" with maximum locally reused, recycled and bio-based materials to reduce the EE consumption; and thirdly, "Design for Disassembly" (DfD), aiming at multi-cycle circular solutions of building materials and components.

2 BACKGROUND ON THE STRATEGIES CONSIDERED IN THIS STUDY

2.1 BIOMIMICRY

Since nature has developed over aeons to provide sufficient solutions, it is the source of our sustenance and has the potential to be the source of answers to most of the challenges humankind faces. Therefore, analysing and mimicking natural strategies can also be a promising scenario for human design challenges. Biomimicry is the practice of designing and creating artificial replicas of natural phenomena to learn from them and improve upon or replace human-made counterparts.

Biomimicry has already been applied successfully in the built environment, bringing ample opportunities for innovation in engineering and architectural design (Badarnah, 2015). As an example, Figure 2 shows a building located in Harare, Zimbabwe, designed by architect Mick Pearce. Inspired by a termite mound system, this building is entirely cooled by natural ventilation.

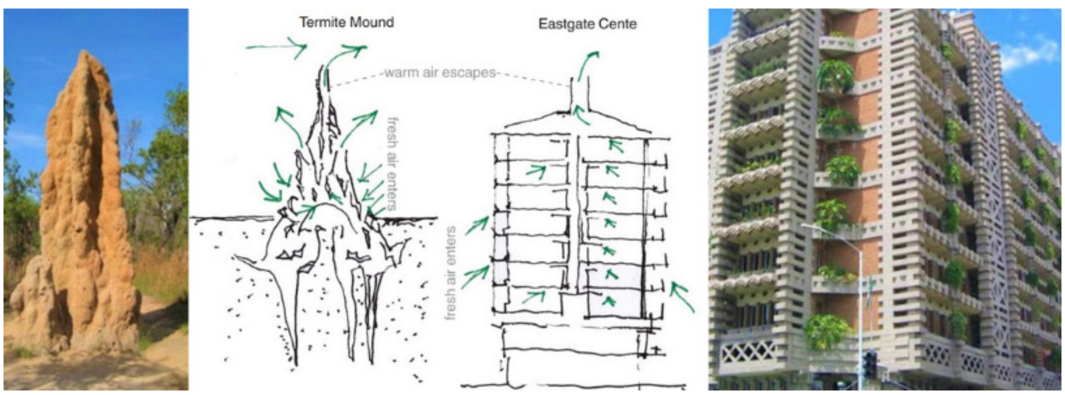


FIG. 2 Ventilation system in a termite mound vs a realised building (Source: (Aithal, 2020; Samimi, 2011))

Buildings' thermal performance, adaptability, and overall OE can all benefit from the application of functional biomimicry (Webb et al., 2018).

2.2 URBAN MINING

Urban mining first appeared with urbanist Jane Jacobs half a century ago. Jacobs estimated that if the metal content in rock continues to decline and the rate of metal resources extracted in the speedy mining increases, it would bring environmental problems and depletion of natural resources. Therefore, she penned the phrase "the cities are the mines of the future" and predicted a situation that is considerably more evident to perceive today (Graedel, 2011).

Even though the concept of urban mining kicked off with the metal extraction insight some time ago, it is widely extended to refer to the process of reclaiming components and elements previously used for buildings, infrastructure, and industries (Cossu & Williams, 2015).

The term "urban mining" is closely linked to the circular economy and offers an idea contrary to the classical "take-use-disposal" approach. It represents the process of recovering and reusing waste materials from urban areas once most of the materials incorporated into cities are disposed of in landfills, incinerated, or downcycled into products of much lower value at the end of their lifespan (Brunner, 2011).

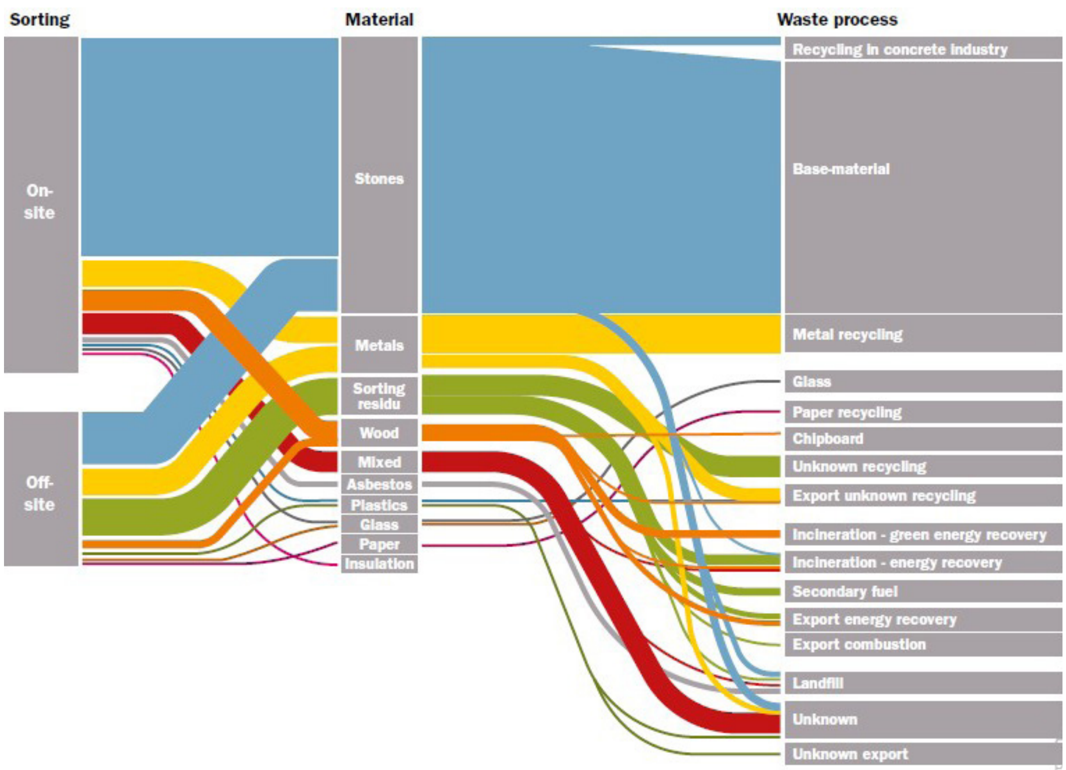


FIG. 3 Material End of Life Sankey diagram in the Netherlands (Source: (TNO, 2018))

In the Netherlands, about 85% of Construction and Demolition Waste (CDW) is downcycled into materials for building foundations, roads, or new residential areas and industrial estates, and only 3% of waste is recycled to construct new buildings (TNO, 2018), as visually represented in Figure 3 with the material end-of-life diagram. This overview reveals a critical improvement needed, and urban mining shows to be a promising strategy to upgrade these rates.

2.3 DESIGN FOR DISASSEMBLY

DfD is a key strategy that guides construction decisions and material selections, altering how elements are connected and structured to be simple, reversible, and resilient, ensuring that building components may be reused or recycled in the most effective manner possible at their end-of-life (Rasmussen et al., 2019). In the built environment, this strategy challenges the current processes, minimising the use of primary materials and maximising the rethinking of the shape of buildings by employing an easy assembly and disassembly technology for the reuse of components and materials.

Different tools have been developed to assess the disassembly level of building elements. For example, Alba Concepts (Mike van Vliet et al., 2019) has developed a methodology to measure the disassembly level. Moreover, the European Level(s) framework and the Belgium GRO framework show similar approaches (European Commission, 2021; GRO, 2022). They form a relevant basis for determining the environmental impact of entire or partial reuse and are directly in line with the end-of-life processing scenarios from LCA calculations.

Building components can only be recovered if they are easily connected to the surrounding building elements. Dry and mechanic connections, such as bolts and screws, are thus more effective than wet and chemical ones, such as glue and mortar (Galle, 2017). Therefore, easy assembly and disassembly design solutions are promising strategies to advance innovation towards a more circular built environment.

3 METHODOLOGY

This chapter is structured as follows: 3.1 describes the boundary conditions for the development of the renovation, such as the characteristics of the existing dwelling type and the available waste demolition materials for the application of urban mining; 3.2 describes the design methodology used throughout the development of the façade design; and 3.3 describes the methods used for assessing the renovation developed in terms of LCEP (3.3.1), such as EE and OE, and DfD (3.3.2).

3.1 BOUNDARY CONDITIONS

3.1.1 Existing dwelling design and structure

In the reconstruction period from 1946 to 1965, after World War II, terraced dwellings were rapidly built all around the Netherlands on a large scale. During that period, no regulations concerning energy performance were imposed (M. J. Ritzen et al., 2016). The choice of materials and design strategies focused on reducing the costs as much as possible, while energy performance was not of significant relevance. According to the governmental Dutch Enterprise Agency (RVO.nl) of the Ministry of Economy, Innovation and Agriculture, 42% of all the dwellings in the Netherlands are terraced dwelling types (Agentschap NL, 2011).

FIG. 4 Existing terraced dwelling (Source: Google maps)

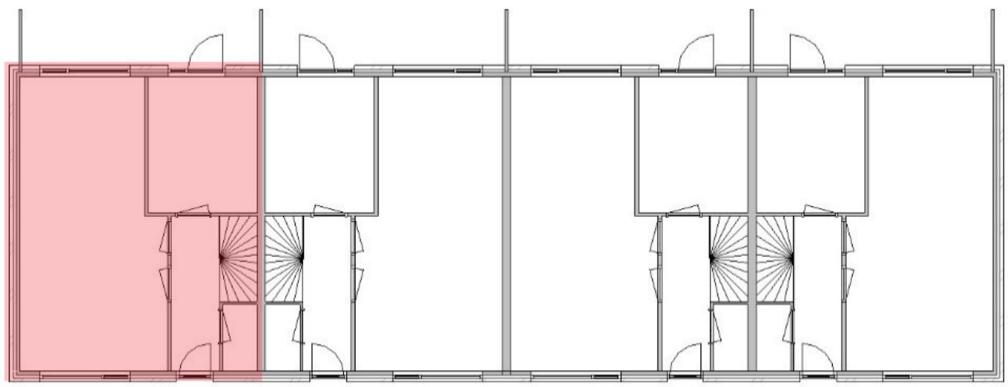


FIG. 5 Floorplan of the dwellings (analysed dwelling highlighted in red)

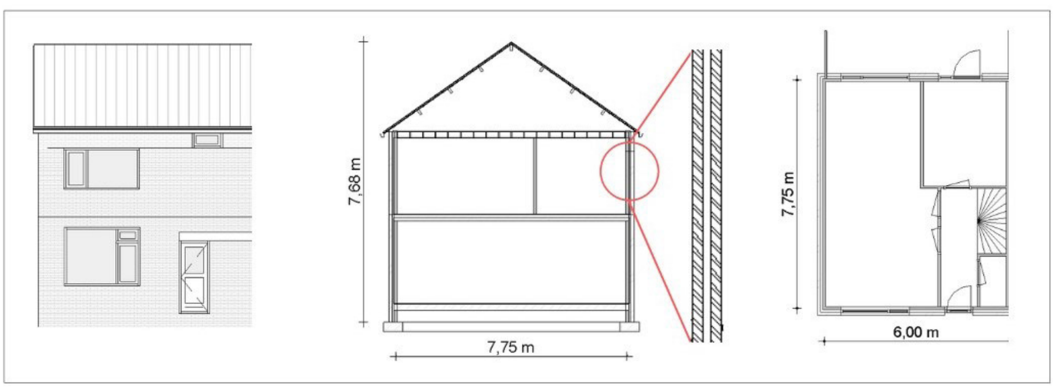


FIG. 6 Existing terraced dwelling: south façade, section, façade structure and floor plan

The selected dwelling for this study is a barely insulated two-floor residential dwelling, as indicated in Figures 4-6 and Table 1. The façade consists of two bricklayers with a ventilated air cavity between them, which does not efficiently insulate the dwelling, resulting in high energy consumption to maintain the inhabitants' thermal comfort. As an outcome, these terraced dwellings consume 41% of all primary energy intended for buildings in the Netherlands (Agentschap NL, 2011).

Moreover, terraced dwellings in the Netherlands are mainly social housing intended for people with lower incomes. Consequently, the reality of most of these houses is a lack of cooling systems, outdated heating systems, such as gas-heated radiators, and low insulation levels.

TABLE 1 Terraced dwelling: general characteristics.

GENERAL CHARACTERISTICS		
Total area	132	m^2
Heated area	81.25	m^2
Orientation front façade	Azimute 0	(North)
Building element	**U-value (W/m^2K)**	
External wall	2.70	
Roof	4.76	
Floors	1.96	
Windows	5.10	
Doors	3.40	

3.1.2 Available materials for renovation

The applicability of the urban mining concept in this study consists of reclaiming demolition materials from a region in the Netherlands called Parkstad, in the southeast of Limburg, Netherlands. The area faces a population decline, which causes a significant demolition assignment of approximately 10,000 dwellings and 150,000 m^2 utility and retail buildings (Stadhouders et al., 2021), resulting in a significant amount of waste materials, as indicated in Figure 7.

Among the materials presented in Figure 7, this study focuses on reusing wood. Firstly, because of the large quantity available (14kton). Secondly, wood has a high thermal resistance, is easy to separate from other building materials, has aesthetical appeal, and can be used in different building segments, such as insulation and construction structures.

Moreover, wood stores CO_2 and consequently can contribute to a low-carbon economy. The CO_2 stored in trees throughout their lifespan is retained in about 50% of the wood's dry weight in wood products. Therefore, the longer the wood remains in the application, the longer the CO_2 is removed from the atmosphere (Friedmann & Kelly, 2003; Petersen & Solberg, 2002; van der Lugt, 2012).

However, it is essential to highlight that critical issues occur when designing and constructing wooden façades, such as ageing treatment, suitable protection from various harmful effects, and fire protection (Herzog et al., 2005; Ivanović-Šekularac et al., 2016).

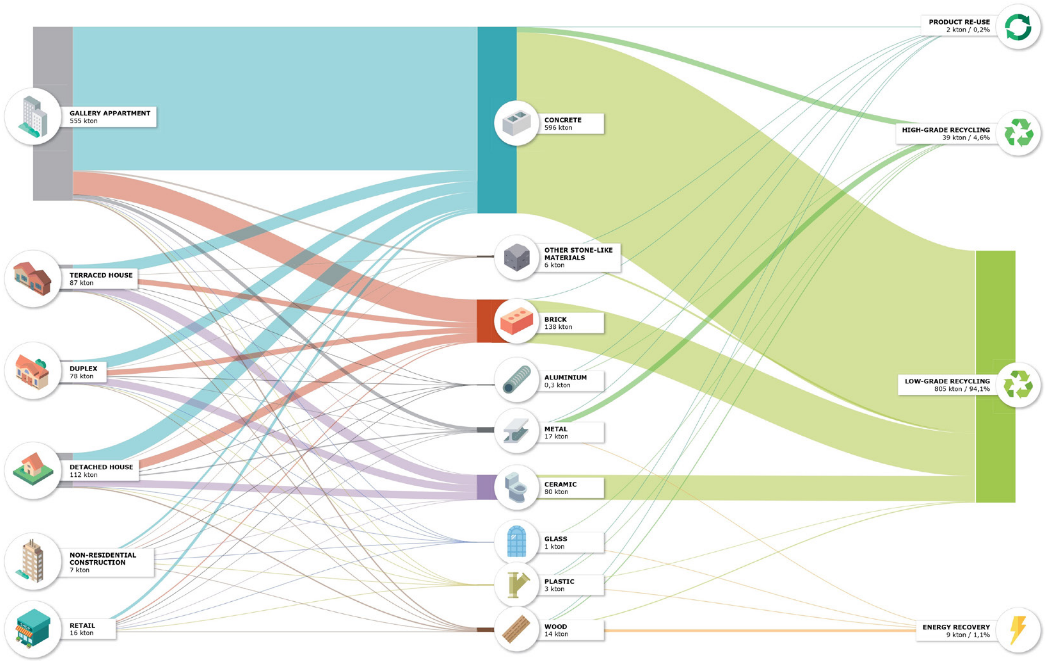


FIG. 7 Materials from demolition in Parkstad (Source: (Stadhouders et al., 2021))

3.2 DESIGN METHODOLOGY

The design methodology of this study follows the strategy of "Research by Design" (Biggs, 2002; Hauberg, 2011; Roggema, 2016; Zimmerman et al., 2007). Generally speaking, employing Research by Design means that the research and the design processes work intertwined; the design is not just a product of research but also a significant component of the research process.

According to Roggema (Roggema, 2016), the Research by Design process can be divided into three parts:

- Pre-design phase: this first stage of a Research by Design process is characterised by understanding;
- Design phase: this is the heart of the process, in which the research is continuously brought into the design process and deliberations;
- Post-design phase: the results are the final syntheses of the work, which must be coherently presented.

The applicability of this methodology strategy in the present study is shown in Figure 8.

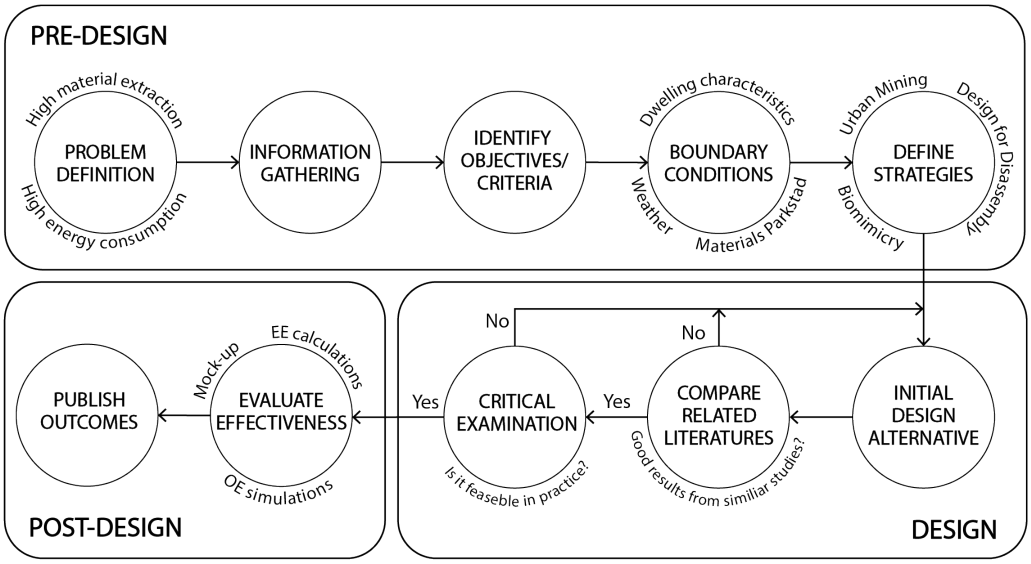


FIG. 8 Research by Design process

3.3 ASSESSMENT METHODOLOGY

This section describes the methodology for assessing the developed façade and the complete dwelling renovation. As previously mentioned, this paper uses the LCEP analysis to evaluate the designed renovation, addressing both the EE and OE (3.3.1) and assesses the developed DfD concept (3.3.2).

3.3.1 Life Cycle Energy Performance

In order to assess the LCEP of the developed renovation, the present study compares OE and EE in three different scenarios:

- Scenario 1: The existing dwelling before renovation (characteristics shown in section 3.1);
- Scenario 2: The renovated dwelling, implementing the developed façade design;
- Scenario 3: Scenario 2 with the addition of 25 m^2 PV modules on the south-orientated roof.

For comparing the three scenarios, a lifespan of 50 years was assumed. The lifespan of a building is both essential and difficult to predict. Generally, the lifespan ranges between 30 and 100 years (Mequignon et al., 2013). The choice of 50 years was based on previous buildings' life cycle studies (Barbara, R. et al., 2012; M. J. Ritzen et al., 2016; Van Ooteghem & Xu, 2012).

The minimal insulation value for façades in the Dutch standard is 4.5 m^{2}K/W (Bowens et al., 2020). However, for comparison with existing products available on the market in subsequent steps of the research, this study is based on an insulation value of at least 7.10 m^{2}K/W.
The conversion from kWh to MJ considered in this research was 5.22, based on system efficiency in the Netherlands (Bowens et al., 2020).

The OE and EE for scenarios 1, 2, and 3 are named OE_1, $OE_{2,}$ OE_3, and EE_1, EE_2, EE_3, respectively.

3.3.1.1 Operational Energy

For the OE assessment, the present study used external literature and the programs *Uniec 2* (Uniec, n.d.) and Photovoltaic Geographical Information System (PVGIS) (European Commission, 2020).

Uniec 2 is an online tool that allows performing energy calculations for buildings based on Dutch regulations. The energy demand calculation is a multi-zone model, and the weather input file and occupancy and schedule for lighting and equipment were based on the NTA 7120. This makes it slightly more difficult to create a realistic picture of a situation but simplifies the program considerably. For the weather input file, *Uniec 2* uses an average and standard climate year, which is provided by NTA 7120. For the occupancy and schedules for lighting and equipment, NTA 7120 has different rules, some of which are related to the size of the building. The energy calculation only applies to building-related installations. Energy for household appliances, such as TVs, fridges, etc., is not included in the calculation. The infiltration load considered is 0.7 dm^3/s per usable area (m^2). As output, the total primary energy consumption of the building is revealed, and the percentage destined for heating, hot water, cooling, summer comfort, ventilation, and lighting is specified.

The energy intended for “summer comfort” provided by *Uniec 2* is a way to alert to the risks of overheating in the summer period. This energy refers to the energy required for cooling features to maintain the building’s summer comfort in overheating periods (Uniec, 2018).

PVGIS is an online free solar PV energy calculator to estimate the solar electricity production of a PV system. PVGIS has been developed by the European Commission Joint Research Centre to disseminate knowledge and data about PV performance and solar radiation. The tool employs high-quality satellite data on solar radiation, ambient temperature, and wind speed from climate reanalysis models. The PVGIS energy model is validated by the Joint Research Centre’s European Solar Test Installation (ESTI). Input data such as location, module type, slope, orientation, and peak PV power are entered into the tool. It then calculates the potential monthly and yearly electricity generation of the specified PV system.

Scenario 1

Firstly, the yearly OE_1 has been calculated using *Uniec 2,* following the characteristics described in 3.1.

Scenario 2

The OE_2 was divided into two parts: firstly, the renovation (without the developed ventilated façade addition) was calculated using *Uniec 2.* In this part, the glazings were changed from single to triple-glazed, and the external doors were changed to insulated wooden doors. Furthermore, 150 mm of insulation was added to the roof and ground floor and 240 mm to the exterior wall. The heating and hot water system were changed from a gas-heated radiator to an air heat pump. The U-values of the new building elements input in *Uniec* are shown in Table 2.

TABLE 2 U-value data input for energy simulation in Uniec.

U-VALUE (W/M^2K)		
Building element	**Scenario 1**	**Scenario 2**
External wall	2.70	0.14
Roof	4.76	0.13
Floors	1.96	0.21
Windows	5.10	1.10
Doors	3.40	2.00

Secondly, regarding the open-joint ventilated façade developed, due to the complexity of existing software, some values to analyse the effect of the ventilated façade on the buildings' energy consumption are based on previous research. Studies with similar designs and technologies present the scenarios' temperature differences, making the predictions of energy savings percentage for the complete building difficult (Sanjuan et al., 2011; Schabowicz & Zawiślak, 2021). Therefore, a review study regarding ventilated façades (Ibañez-Puy et al., 2017) was used to define the expected energy percentage reduction destined for summer comfort with the addition of a ventilated façade.

Scenario 3

25 m^2 of PV modules (320 Wp/panel or 200 Wp/m^2 (Innodura, 2021)) on the south-orientated roof was included, corresponding to the available area of the south-oriented roof, resulting in a peak PV power of 5 kWp. The output energy per year from the PV modules implementation was calculated using PVGIS and discounted from the OE_2.

3.3.1.3 Embodied Energy

The EE of the three different phases of renovation were calculated through a cradle-to-gate assessment, which is an analysis of a portion of the product life cycle, starting with the resource extraction (cradle) and ending at the factory gate (before transportation to the consumer) (C.Cao, 2017). It is considered the energy spent for material extraction or harvest and the energy spent for the manufacturing process, as shown in Figure 9. Therefore, this study did not consider the energy used for the transportation of the material, the energy spent during the building assembly, the energy used for maintenance during the usage phase, and the energy consumption related to the end-of-life phase.

Firstly, the three scenarios were accurately modelled in *Autodesk Revit*, with the precise dimensions of the components, and the volumes of each material used in the models were calculated by Revit. Secondly, after having the density and materials' volume in the three scenarios, the EE in MJ/kg of each material was determined by gathering information from material suppliers, literature reviews, and the "ICE database".

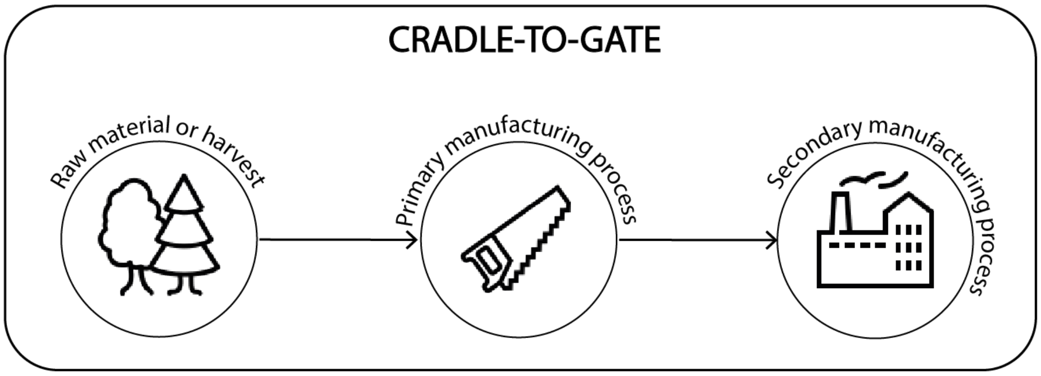


FIG. 9 Cradle-to-gate assessment scheme

The ICE database is a spreadsheet format developed by Geoff Hammond and Craig Jones from the Sustainable Energy Research Team (SERT) of the Department of Mechanical Engineering of the University of Bath (UK) (SERT, 2011), which compares different alternatives and calculates the environmental impact of components. It includes LCA information on the material or component levels and provides the EE [MJ/kg] and ECO_2 [$kgCO_2/kg$] of the most common construction materials utilised in the built environment (Bach & Hildebrand, 2018) based on the cradle-to-gate assessment. The database was selected by the consortium of a European research project.

The total EE from scenario 1 (EE_1) is the total of all EE from all materials that compose the existing terraced dwelling. The EE in scenario 2 (EE_2) is EE_1 discounting all the EE referent to the components demolished or changed in the renovated scenario, plus the energy related to the manufacturing of façade components. The calculation of EE in scenario 3 (EE_3) is the sum of EE_2 and the EE required for the PV modules extraction, manufacturing, and construction ($EE_{PV\ modules}$).

3.3.2 Design for Disassembly

The methodology adopted to assess the DfD index of the proposal was based on Alba Concepts (Mike van Vliet et al., 2019) and ISSO assessment (ISSO, 2021).

This method assesses the DfD index of a product, both in the end-of-life and the maintenance scenarios, by analysing the connections within its components based on four aspects: connection type, accessibility of the connection, piercing, and inclusion.

The “end-of-life” scenario refers to a situation where the complete structure is either demolished or disassembled. It evaluates the element’s potential to be reused for a new application in a new building. It depends on the product quality after use and how damage-free the product can be removed (disassembly). For that, the elements are assessed by their type and accessibility of connections.

The “maintenance” scenario refers to a situation in which one or more components of the structure will be removed or replaced during the lifespan of the building. It is assumed that every element will be removed individually. Therefore, besides the connection’s type and accessibility, the piercing and inclusion in its original positions in the building are also considered.

A connection can be valued at 0.1 - 1.0 according to its characteristics, with 0.1 giving the lowest rating for DfD and 1.0 the highest, as shown in Table 3. The average of these four scores determines the DfD level of the element in question. The weighted average of all the elements used in a building together constitutes the DfD Index of a building.

TABLE 3 Ranking for scoring an element connection for the DfD assessment.

TYPE OF CONNECTION		SCORE
Dry connection	Dry connection	1
Click connection	Dry connection	1
Velcro connection	Dry connection	1
Magnetic connection	Dry connection	1
Bolt and nut connection	Connection with added elements	0.8
Spring connection	Connection with added elements	0.8
Corner connection	Connection with added elements	0.8
Screw connection	Connection with added elements	0.8
Connection with added elements	Connection with added elements	0.8
Pin connection	Direct integral connection	0.6
Nail connection	Direct integral connection	0.6
Lute connection	Soft chemical bond	0.2
Foam connection (PUR)	Soft chemical bond	0.2
Glue connection	Hard chemical bond	0.1
Pouring joint	Hard chemical bond	0.1
Welded connection	Hard chemical bond	0.1
Cement bound connection	Hard chemical bond	0.1
Chemical anchors	Hard chemical bond	0.1
Hard chemical bond	Hard chemical bond	0.1
Accessibility of connection		**score**
Freely accessible		1
Accessible with actions that don't cause damage		0.8
Accessible with actions that cause repairable damage		0.4
Not accessible - irreparable damage to objects		0.1
Inclusion		**score**
Open, no inclusion		1
Overlap		0.8
Closed (on one side)		0.2
Piercing		**score**
No piercing		1
Piercing by one or more objects		0.4
Full integration of objects		0.1

4 RESULTS

This chapter is structured as follows: 4.1 discusses the design process (clarifying the reasons for each choice) and describes the final façade design; 4.2 reports the assessment in terms of LCEP of the three different scenarios; 4.3 shows the DfD assessment of the developed façade design.

4.1 FAÇADE DESIGN

The first part of the energy renovation proposal for the existing dwelling consists of added insulation on the façade structure. The proposed insulation addition does not only focus on improving the energy performance of the building but also on reusing the materials from demolition (urban mining) in its manufacturing process. In other words, this study defines the available materials at the demolition site that can potentially be transformed into an insulation material, which filtered the analyses between the use of glass (fibreglass) or wood (cellulose fibre and wood fibre). These options were then compared in terms of thermal conductivity, EE, and fire class, as indicated in Table 4.

TABLE 4 List of insulation materials and properties to be compared.

INSULATION MATERIALS			
Material	**λ (W/mK)**	**EE (MJ/kg)**	**Fire Class**
Cellulose Fibre	0.041	0.94 - 3.3	B
Wood Fibre	**0.038**	**10.8**	**D**
Fibreglass	0.033	28	B

Firstly, cellulose fibre shows the best results in terms of EE. However, the current manufacturing process of cellulose fibre is based on downcycling newspapers, and the process of reusing cellulose fibre from wood waste is not yet developed. As this study focuses on reusing the available materials from demolition waste, this option was discarded.

Regarding fibreglass insulation, it is the best among the options in terms of thermal conductivity, and glass is one of the listed materials available at the demolition site. However, its EE is the highest among the materials analysed.

Thus, wood fibre insulation has shown to be the best option. If it can be made from wood waste from demolition (available at a rate about 14 times higher than glass), it has an outstanding performance in terms of thermal conductivity (around 0.038 W/mK), and its EE is almost three times lower than that of fibreglass. An ambitious alternative for the production process of wood fibre insulation could be the reuse of the sawdust produced during the manufacturing of the wooden structure.

However, since this material has fire class D, some strategies should be adopted to improve the fire resistance of the whole construction. Most of the alternatives to overcome this hindrance are related to adding chemicals into the insulation material, such as boric acid (Veitmans & Grinfelds, 2016), contradicting the idea of the circular analysis, bringing harmful consequences into the environment, and carrying high collateral EE (An & Xue, 2014; Cusenza et al., 2021). As a potential alternative, using fire-resistant boards (such as fibre cement) on the outsides of the insulation material was the chosen solution for this research.

After defining the insulation material to be used, the discussion relates to how this wood fibre insulation would be placed on the existing façade. As presented previously, the current façade consists of two brick layers with an air cavity between them. Therefore, the insulation material could be applied in three ways in the cavity wall, as shown in Figure 10.

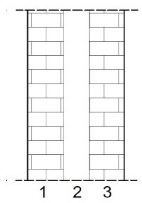
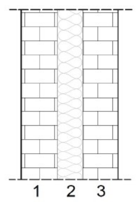
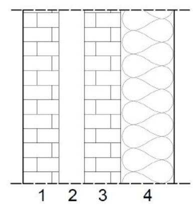
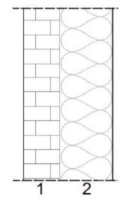
	CURRENT CONDITION	POSSIBILITIES		
Wall Structure				Demolish one brick layer 
	1 Brick 100 mm 2 Ventilated air cavity 70 mm 3 Brick 100 mm	1 Brick 100 mm 2 Insulation 70 mm 3 Brick 100 mm	1 Brick 100 mm 2 Ventilated air cavity 70mm 3 Brick 100 mm 4 Insulation 240mm	1 Brick 100 mm 2 Insulation 240mm
Thickness (mm)	270	270	510	340
Rc (m²K/W)	0.37	2.27	7.14	7.14
U (W/m²K)	2.70	0.44	0.14	0.14

FIG. 10 Comparison of different insulation settlements

Firstly, it could be placed between the two brick layers; however, the void of 70 mm is not enough to reach the Dutch standard of 4.5 m^2K/W as a minimal Rc (Bowens et al., 2020). Secondly, the insulation could be placed in front of the double-brick façade; however, the wall would be very thick and unrealistic from a practical perspective. Therefore, the option that would meet the requirements consists of demolishing the external brick layer and placing the insulation outside of the single brick layer. The red and green cells in Figure 10 represent the values that do not meet the requirements and those that meet the requirements, respectively.

Thus, 240 mm of wood fibre insulation was placed on the outer part of the single-brick wall, and 150 mm of insulation was added to the roof and ground floors, as shown in Figure 11.

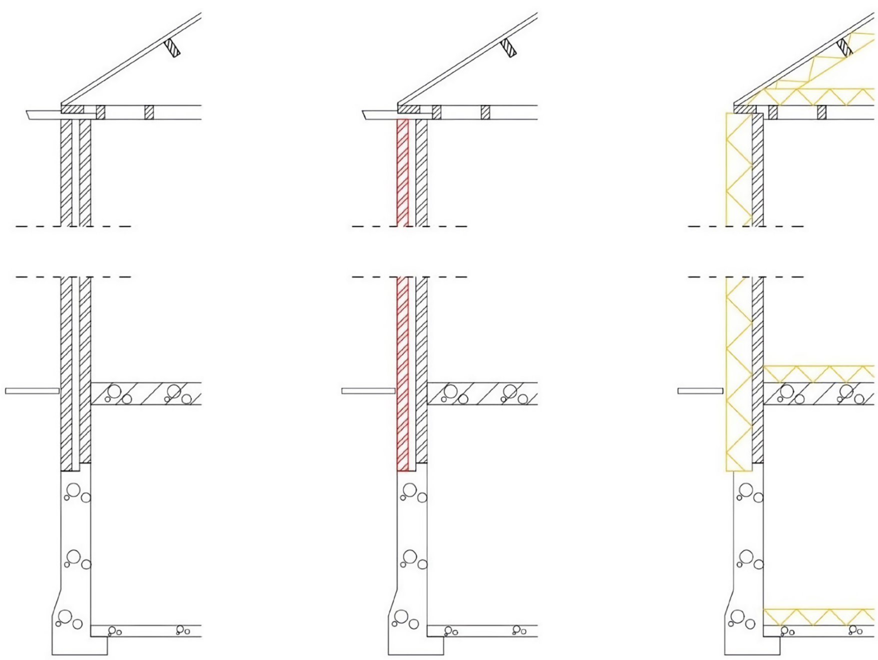


FIG. 11 Insulation addition and structure of renovated wall (existing façade in grey, the brick layer to be demolished in red, and the new insulation addition in yellow)

However, this arrangement raises the need to think about a structure to which this insulation can be attached. When analysing the demolition site, a significant number of wooden beams from existing roof structures will be discarded after demolition in Parkstad.

Aiming at reusing these wooden beams in the least processed manner possible, this study proposes sawing the beams into two parts and using them directly as the structure for the insulation material. The proposed process from the roof structure (waste from demolition) to the insulation structure is shown in Figure 12.

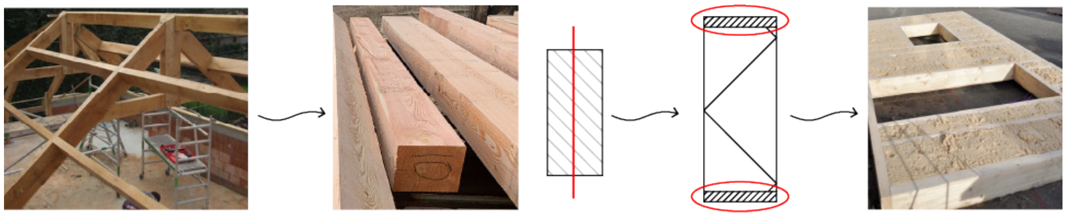


FIG. 12 Urban mining process: wooden structure for insulation

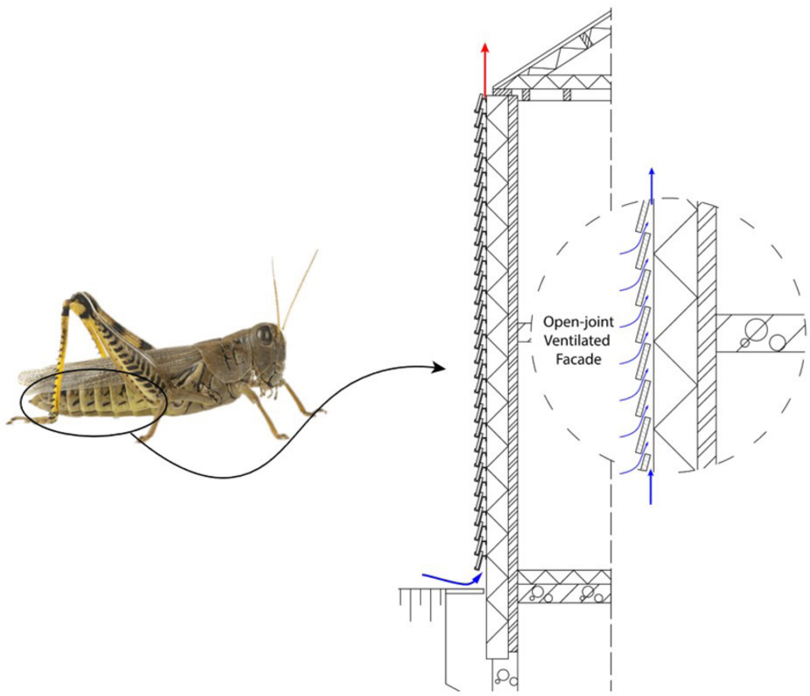


FIG. 13 Final concept of façade design inspired by cricket's openings

After developing an insulation application based on the urban mining strategy, a open-joint ventilate façade based both on the urban mining and biomimicry concepts was developed in this study.

Ventilated façades work as follows: the cool air enters through the bottom opening, and air pressure pushes out the hot air through the top opening. The developed open-joint ventilate façade works similarly. However, in the developed ventilated façade, openings were applied throughout the height of the façade, as the design was inspired by the openings of the cricket's respiratory system, as shown in Figure 13. Thus, the façade's final structure consists of a single brick layer, an insulation element and structure, an air cavity, and an additional external wooden skin.

Moreover, following the urban mining concept, the external skin of the ventilated façade was developed by reusing the wooden beams from demolition. As shown in Figure 14, the wooden beams from the roof structure were sawed into two parts, and the wooden slabs were placed along the façade length with a space between them for air circulation.

FIG. 14 Urban mining process: ventilated façade

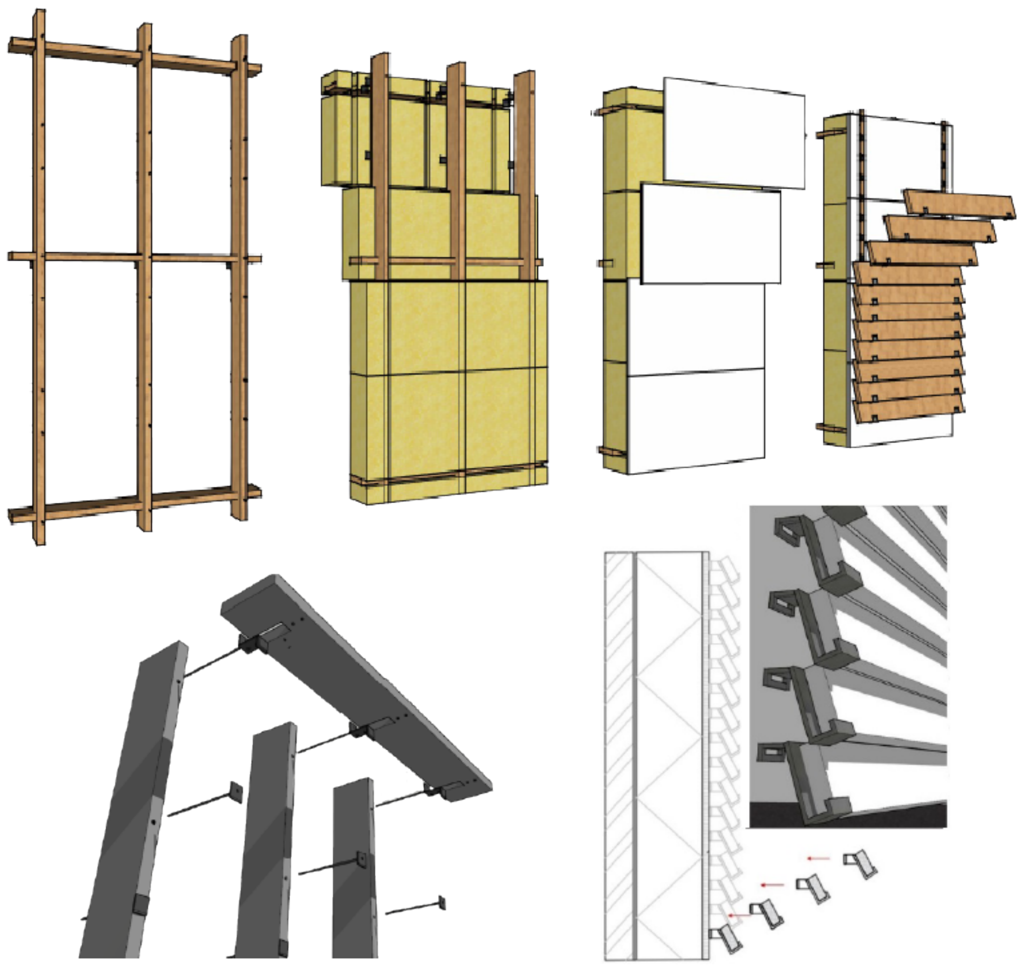


FIG. 15 Easy and dry assembly, based on the concept of DfD

Nevertheless, using wood as a cladding material has several problems due to its exposure to external weather conditions, such as accelerated ageing and mould infestation. With a focus on avoiding the use of chemicals in preventing these harmful effects, the study proposes using heat treatment for ageing and moisture control. As reviewed by (Esteves & Pereira, 2008), the heat treatment enhances the wood's resistance to insects and increases durability.

Finally, the whole façade renovation was also based on the previously discussed concept of DfD, with an easy assembly and disassembly method to reduce tenants and neighbourhood disturbance as much as possible, guarantee a fast and clean construction, and enable the reuse of components.

The strategy consists of using a pre-moulded insulation structure fastened with screws. The cladding material for the ventilated façade will be placed using a hook system, avoiding any use of glue or mortar. The assembly method is shown in Figure 15.

4.2 LCEP CALCULATIONS

4.2.1 Operational Energy

In scenario 1, the yearly energy calculations performed using *Uniec* indicated that the OE of the existing dwelling is 1.38E+05 MJ/year, as shown in Figure 16. Thus, **OE1 = 6.88E+06 MJ** over a lifespan of 50 years.

This result is equivalent to 324.20 kWh/m^2/year, considering a kWh to MJ conversion of 5.22 and the previously mentioned heated area of 81.25 m^2.

SCENARIO 1

Primary energy consumption	MJ/year	MJ (50 years)	%
Heating	1.11E+05	5.54E+06	81
Hot water	1.50E+04	7.49E+05	11
Cooling	-	-	0
Summer comfort	5.09E+03	2.55E+05	4
Ventilation	2.98E+03	1.49E+05	2
Lighting	3.74E+03	1.87E+05	3
Total	**1.38E+05**	**6.88E+06**	100

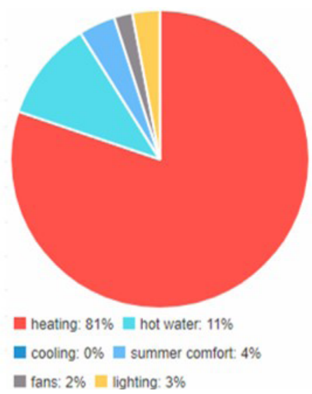


FIG. 16 Scenario 1: OE consumption and the percentage calculated in Uniec

In scenario 2, before considering the ventilated façade, the *Uniec* simulation indicates an OE consumption of 2.07E+04 MJ/year, which reduces 81.8% of the OE_1. The percentage distribution of the energy use is shown in Figure 17. The total energy consumed per dwelling is approximately **1.03E+06 MJ** over 50 years.

SCENARIO 2			
Primary energy consumption			
	MJ/year	MJ (50 years)	%
Heating	4.86E+03	2.43E+05	23
Hot water	9.46E+03	4.73E+05	46
Cooling	-	-	0
Summer comfort	2.10E+03	1.05E+05	10
Ventilation	5.17E+02	2.59E+04	2
Lighting	3.74E+03	1.87E+05	18
Total	**2.07E+04**	**1.03E+06**	100

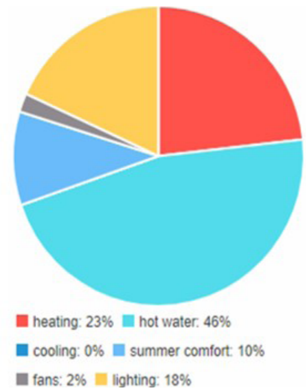


FIG. 17 Scenario 2: OE consumption and the percentage calculated by Uniec

After simulating the energy required in scenario 2 without the ventilated façade, the effect of the ventilated façade is considered. The summer comfort corresponds to 10% of all the energy consumption in scenario 2, as shown in Fig 17. As reviewed by (Ibañez-Puy et al., 2017), the ventilated façade studies typically include energy savings in summer periods exceeding 40%. Therefore, considering a 40% reduction of summer comfort energy, there will be a reduction of 840 MJ/year and **4.20E+04 MJ** over 50 years. Thus, the total OE of scenario 2 corresponds to:

$$OE_2 = 1.03E{+}06 - 4.20E{+}04$$

$$\mathbf{OE_2 = 9.88E{+}05}$$

This result is equivalent to 46.78 kWh/m^2/year, considering a kWh to MJ conversion of 5.22 and the previously mentioned heated area of 81.25m^2.

Finally, in scenario 3, the output energy was calculated considering the PV technology Crystalline Silicon, as indicated in Table 5.

TABLE 5 Scenario 3: Energy output from PV modules

PV PANELS - ENERGY GENERATION					
Orientation	**PV size**	**Output Energy**		**Lifespan**	**TOTAL**
	(m^2)	**(kWh/year)**	**(MJ/year)**	**(years)**	**(MJ)**
South (180)	25	5.12E+03	2.67E+04	50	1.34E+06

The energy output from the PV modules is discounted in the OE from scenario 2. As a result, the total OE associated with scenario 3 is:

$$OE_3 = OE_2 - OE_{\text{PV modules}} = 9.88E{+}05 - 1.34E{+}06$$

$$\mathbf{OE_3 = -\ 3.52E{+}05\ MJ}$$

This result is equivalent to -16.60 kWh/m^2/year, considering a kWh to MJ conversion of 5.22 and the previously mentioned heated area of 81.25m^2.

A negative OE means that the building generates more energy than it consumes. In other words, the energy generated from the PV modules installed in the building is higher than the energy required for maintaining the building, such as lighting, heating, cooling, and hot water. However, for a complete overview of the building's LCEP and to analyse whether this scenario does indeed generate more energy than it consumes over 50 years, EE should also be addressed.

4.2.2 Embodied Energy

For scenario 1, Table 6 lists all the materials in the terraced dwelling, its volume, and associated EE following the previously discussed methodology. The calculations result in a total **EE_1 = 2.60E+05 MJ** for the existing scenario.

TABLE 6 Scenario 1: Calculation of existing EE.

BUILDING COMPONENT	MATERIALS	QUANTITY	DENSITY	TOTAL AMOUNT OF MATERIALS	DATA FROM ICE INVENTORY	
	Description of each material	**Amount Revit (4 dwellings) [m^3]**	**Unit of measure [kg/m^3]**	**Per dwelling [kg]**	**Embodied Energy [MJ/kg]**	**Embodied Energy [MJ]**
Foundation	Basement walls (0,03m thick)	1.97E+01	2.40E+03	1.18E+04	9.90E-01	1.17E+04
	Basement floor (0,08m thick)	4.12E+00	2.40E+03	2.47E+03	9.90E-01	2.45E+03
	Foundation slabs 600x300mm	1.19E+01	2.40E+03	7.11E+03	7.10E-01	5.05E+03
	Foundation slabs 300x300mm	1.16E+00	2.40E+03	6.96E+02	7.10E-01	4.94E+02
Opaque façades	Internal bricks	3.07E+01	1.70E+03	1.30E+04	3.00E+00	3.91E+04
	External bricks	3.17E+01	1.90E+03	1.50E+04	3.00E+00	4.51E+04
Roof	2 wall plates (50x155mm)	3.69E-01	5.10E+02	4.70E+01	1.00E+01	4.70E+02
	1 ridge purlin (80x180mm)	3.50E-01	5.10E+02	4.46E+01	1.00E+01	4.46E+02
	6 purlins (65x165mm)	1.57E+00	5.10E+02	2.00E+02	1.00E+01	2.00E+03
	Roof underlayment (18mm thickness)	4.37E+00	5.10E+02	5.57E+02	1.00E+01	5.57E+03
	Roof beams (25x38mm)	9.37E-01	5.10E+02	1.19E+02	1.00E+01	1.19E+03
	Roof tiles ceramic (12mm thickness)	2.91E+00	2.00E+03	1.45E+03	1.00E+01	1.45E+04
Frames, doors, windows	Wooden frames for windows and doors (façades)	1.41E+00	5.10E+02	1.80E+02	1.00E+01	1.80E+03
	Internal wooden sill	8.02E-01	5.10E+02	1.02E+02	1.00E+01	1.02E+03
	Internal doors and frames	2.58E+00	5.10E+02	3.29E+02	1.20E+01	3.94E+03
	Glass panels 3.2mm thick	2.80E-01	2.50E+03	1.75E+02	1.50E+01	2.63E+03

>>>

TABLE 6 Scenario 1: Calculation of existing EE.

BUILDING COMPONENT	MATERIALS	QUANTITY	DENSITY	TOTAL AMOUNT OF MATERIALS	DATA FROM ICE INVENTORY	
	Description of each material	**Amount Revit (4 dwellings) [m³]**	**Unit of measure [kg/m³]**	**Per dwelling [kg]**	**Embodied Energy [MJ/kg]**	**Embodied Energy [MJ]**
Internal ground floor	Internal ground floor concrete (200mm thick)	3.40E+01	2.40E+03	2.04E+04	7.50E-01	1.53E+04
	Floor finish ("plasterboard") 20mm thick	3.10E+00	1.90E+03	1.47E+03	4.51E+00	6.65E+03
Internal first-storey floor	Internal first-storey floor concrete (200mm thick)	3.40E+01	2.40E+03	2.04E+04	7.50E-01	1.53E+04
	Floor finish ("plasterboard") 20mm thick	3.10E+00	1.90E+03	1.47E+03	4.51E+00	6.65E+03
Internal second floor	Wooden floor structure	2.06E+00	5.10E+02	2.63E+02	1.00E+01	2.63E+03
	Floor finish ("wooden floor") 18mm thick	2.90E+00	5.10E+02	3.70E+02	1.00E+01	3.70E+03
Internal walls	Internal bricks wall (200mm thick)	3.26E+01	1.70E+03	1.39E+04	3.00E+00	4.16E+04
	Internal bricks wall (100mm thick)	1.19E+01	1.70E+03	5.05E+03	3.00E+00	1.51E+04
	Internal bricks wall (70mm thick)	8.32E+00	1.70E+03	3.54E+03	3.00E+00	1.06E+04
Stairs	Wooden structure	3.47E+00	5.10E+02	4.42E+02	1.00E+01	4.42E+03
1. Dutch demonstrator (surface: 132.82 m²)					**EE1 =**	**2.60E+05**

In scenario 2, the EE calculation considers EE_1 and discounts the changes promoted by the wall demolition, wooden frames, insulation material, ventilated façade, heating and hot water systems, and new windows and frames.

Firstly, since the external façade brick layer is demolished and the windows and frames are changed, the EE from the external brick layer (4.51E+04), glass panels (2.63E+03), and façade frames (1.80E+03) shown in Table 6 were not considered in the "Existing" phase of EE_2, resulting in 2.10E+05.

Secondly, for calculating the EE associated with the wooden structure, the energy necessary to saw the wood was considered. According to (Nwuba & Kaul, 1987), the energy required to saw the wood with a power chain is 3.8kJ/min. The sawing process takes approximately four hours, resulting in a consumption of 0.91MJ.

Regarding the wood fibre insulation material, the values from the ICE database were considered: EE of 10.8 MJ/kg and density of 40kg/m³. The total volume of insulation necessary is 41.26m³, resulting in an EE of 17,825.18 MJ.

As previously mentioned, for the cladding material of the ventilated façade, the beams from the demolition site undergo a sawing and heat treatment process, both of which are included in the calculation. Firstly, the energy required for sawing the wood was considered the same for sawing the wooden structure (0,91MJ). The heat treatment was considered a thermal modification, with the volume of wood about 3.32 m^3. According to (Candelier & Dibdiakova, 2021), the EE associated with this treatment is 2830 kWh/m^3, based on kWh to MJ conversion of 5.22 (Bowens et al., 2020), corresponding to 14,772.60 MJ/m^3, resulting in 48,999.18 MJ.

The new heating and hot water system adopted is the air heat pump. The energy required for this system is calculated in Table 7.

TABLE 7 EE calculation of air heat pump.

EE - AIR HEAT PUMP			
Material	**Amount (kg)**	**EE (MJ/kg)**	**Total EE (MJ)**
Low alloyed steel	32	56.7[1]	1814.4
Reinforced steel	120	56.7[1]	6804
Copper	36.6	57[1]	2086.2
Elastomere	16	102.1[1]	1633.6
Polyvinylchloride	1.6	77.2[1]	123.52
Polyolester oil	2.7	37.28[2]	100.656
HDPE	0.5	76.7[1]	38.35
R-134a (20 yrs)	13.3	26.508[3]	352.5564
Total			**1.30E+04**

1 *ICE database 2011*

2 *Energy Demand and Greenhouse Gases Emissions in the Life Cycle of Coffee Harvesters lubricant oil*

3 *1430 kg CO_2: International Energy Agency / Evaluation of Embodied Energy and CO_2eq for Building Construction (Annex 57); 6,6 kg CO_2: From mine to refrigeration: a life cycle inventory analysis of the production of HFC-134a*

The energy values associated with the new windows and frames are provided by the manufacturer. Thus, Table 8 shows the final EE of scenario 2, considering all the processes and materials mentioned for this scenario.

TABLE 8 Scenario 2: EE calculation.

RENOVATED SCENARIO		
2.1	Existing	2.10E+05
2.2	Wooden frames	9.12E-01
2.3	Insulation	1.78E+04
2.4	Ventilated façade	4.90E+04
2.5	Heating and hot water system	1.30E+04
2.6	Windows, door, frames	1.11E+04
	TOTAL EE2 (MJ)	**3.01E+05**

Finally, for scenario 3, the EE associated with the PV modules is indicated in Table 9.

TABLE 9 EE from PV modules (Source: (Michiel J. Ritzen, 2017)).

EE - PV MODULES				
EE extraction (MJ/m^2)	EE manufacturing (MJ/m^2)	EE construction (MJ/m^2)	Area (m^2)	TOTAL EE (MJ)
600	1488	13	25	**5.25E+04**

Thus, the EE of scenario 3 is the sum of the previous EE_2 and the EE of the PV modules:

$$EE_3 = EE_2 + EE_{\text{PV modules}} = 3.01E+05 + 5.25E+04$$

$$\mathbf{EE_3 = 3.53E+05\ MJ}$$

4.2.3 Total LCEP

After calculating the OE and EE for each scenario, the total LCEP per scenario can be calculated and compared based on:

$$\text{Life Cycle Energy} = \text{Embodied Energy} + \text{Operational Energy}$$

Figure 18 and Table 10 show the values calculated of EE and OE from each scenario, with the reduction percentage compared to the existing situation (scenario 1).

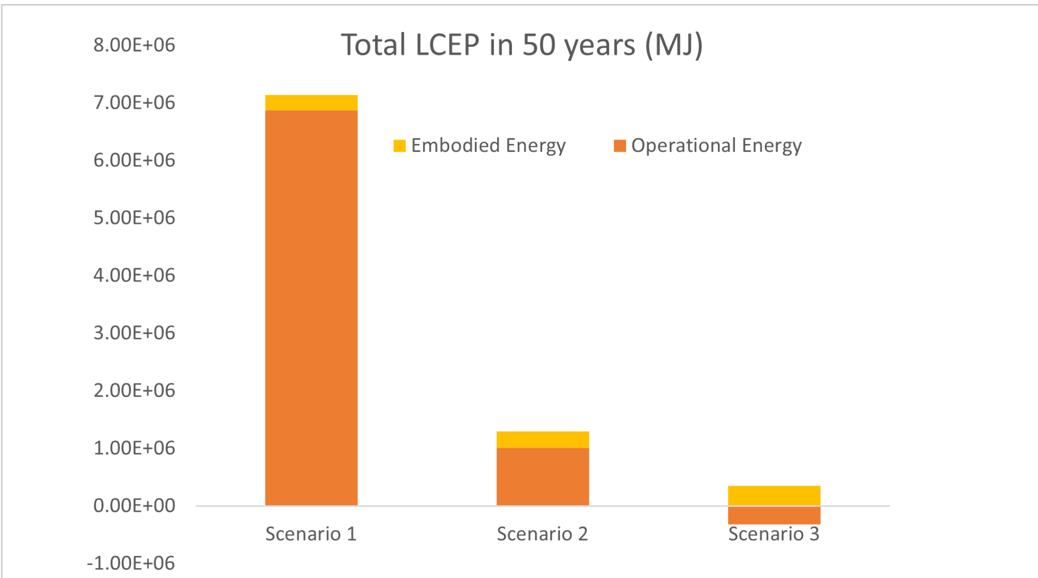


FIG. 18 Total LCEP of each scenario, accounting for OE and EE

TABLE 10 Total LCEP of each scenario, accounting for OE and EE, with the reduction percentage.

TOTAL LCEP IN 50 YEARS (MJ)			
	Scenario 1	**Scenario 2**	**Scenario 3**
Operational Energy	6.88E+06	9.88E+05	-3.49E+05
Embodied Energy	2.60E+05	3.01E+05	3.53E+05
Total LCEP	7.13E+06	1.29E+06	4.82E+03
Reduction	0%	81.9%	99.9%

4.3 DESIGN FOR DISASSEMBLY ASSESSMENT

The DfD index calculated for end-of-life and maintenance results in 0.86/1.0 and 0.95/1.0, respectively, as shown in Figure 19.

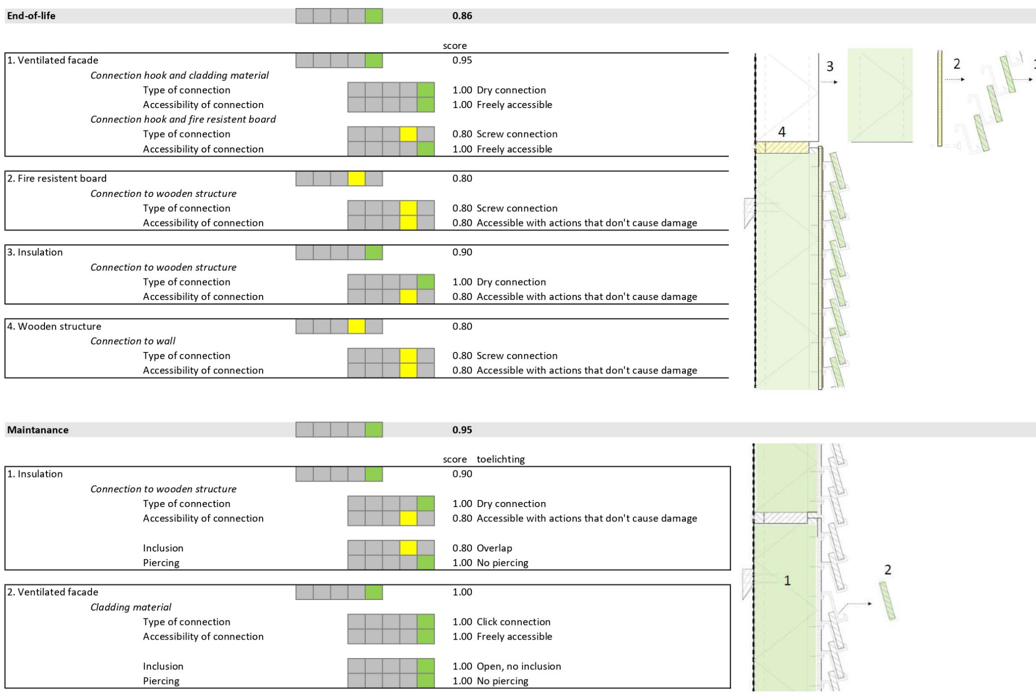


FIG. 19 DfD index of developed façade design

5 DISCUSSIONS

Renovating the building stock is a potential key aspect toward an energy-neutral built environment. Literature shows that the OE has a more significant effect on the overall LCEP. However, with the increasing attention and improvements regarding this concern, the EE is becoming increasingly relevant. Therefore, OE and EE, in conjunction, are vital indices in assessing the complete environmental impact of a building.

Concerning the EE calculations and the use of the ICE database, some limitations and uncertainties exist since the ICE dataset refers to the United Kingdom, and the version applied is not up-to-date. However, as this is a comparative study in an international context, this is not a very relevant shortcoming. If an absolute answer is needed, a national database such as Nationale Milieudatabase (NMD, 2020) could be used in a particular context.

Regarding the wood fibre insulation, there was a lack of information concerning the fire resistance treatment in a circular and/or bio-based way. Through literature reviews, the options were mainly related to using chemicals with high EE to improve the fire class of the material.

Furthermore, reusing the wood straight from the demolition site to produce the wood fibre insulation is still very theoretical, and studies concerning the process of upscaling still need to be investigated.

Since scenario 1 of this paper corresponds to approximately 42% of the dwellings in the Netherlands, the importance of this research is related to the possibility of upscaling the renovation of these dwellings. It would bring significant energy savings and, consequently, a significant reduction in CO_2 emission rates.

FIG. 20 Mock-up developed for results validation

As the next step in this research, a mock-up has been developed to validate the results, as shown in Figure 20. In this mock-up, the designed façade is compared with already existing ventilated façade products in the market and the existing façade (as scenario 1). In this mock-up, the circular aspects related to the reuse of wood from demolition and the DfD strategies are fully considered, also working to evaluate the urban mining and the assembling and disassembling processes.

6 CONCLUSIONS

As a result of the complete design, scenario 2 presents a reduction of 82% in the total LCEP, and scenario 3 shows a 100% reduction in the LCEP. This means that the Zero Energy Building was achieved with the renovation proposed in scenario 2 and the addition of PV modules in scenario 3. Nevertheless, the developed ventilated façade does not bring positive results for the LCEP when applied in combination with the complete building renovation (scenario 2) and in the Dutch weather characteristics. Contrariwise, the results show an EE of the ventilated façade (4.90E+04 MJ) higher than the OE savings due to the ventilated façade (4.20E+04 MJ) in a lifespan of 50 years. It signifies that the energy spent for manufacturing the ventilated façade was higher than its effect on the energy reduction and, therefore, not beneficial for the conditions applied in scenario 2.

There are two ways to analyse this result: firstly, in the renovated scenario (scenario 2), the energy destined for summer comfort is a small percentage of the overall building's energy consumption (10%). It means that the ventilated façade would bring better results in scenarios where the energy for maintaining summer comfort is higher, such as in countries with warmer weather and in a future perspective due to climate change and temperature increment.

Secondly, suppose the developed ventilated façade is added separately to the existing dwelling (scenario 1). In that case, the OE savings due to the ventilated façade (40% * 2.55E+05 MJ = 1.02E+05 MJ) is greater than the energy required for manufacturing (4.90E+04 MJ). Thus, if the developed ventilated façade is applied individually to an existing dwelling with low energy performance, the results are positive even in the Dutch scenario.

The DfD index for the developed façade design presents high results for the end-of-life (0.86/1.0) and maintenance (0.95/1.0) analysis. This indicates that the developed ventilated façade technology and wooden structure can be an innovative alternative to strengthen the circular built environment concept and deal with construction and demolition waste. However, future research should still study the trade-off between LCEP and DfD.

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