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To cite this article: Delphine Ramon and Karen Allacker 2023 *Environ. Res.: Infrastruct. Sustain.* **3** 045010

ENVIRONMENTAL RESEARCH
INFRASTRUCTURE AND SUSTAINABILITY

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OPEN ACCESS

RECEIVED
14 July 2023

REVISED
19 November 2023

ACCEPTED FOR PUBLICATION
8 December 2023

PUBLISHED
20 December 2023



PAPER

# Optimizing building solutions in a changing climate: parameter-based analysis of embodied and operational environmental impacts

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**Keywords:** climate change, building design, embodied emissions, operational emissions, life cycle assessment, parametric analysis

Supplementary material for this article is available online

## Abstract

Buildings contribute significantly to global energy consumption and carbon dioxide emissions. Climate change affects building performance, particularly heating and cooling demands. While current policies focus on improving energy performance and reducing operational emissions, the embodied emissions from building materials become more significant in energy-efficient buildings. This study aims to investigate optimal building solutions considering both operational and embodied environmental impact in the context of climate change in the Belgian context. The research questions address the influence of building characteristics on environmental impact and the contribution of embodied and operational emissions to optimal design. The study employs parametric life cycle assessment and dynamic building energy simulation to explore design strategies for a medium-sized office building. The results reveal the trade-offs between operational and embodied impacts. Buildings with better energy performance exhibit higher embodied emissions, highlighting the importance of considering both aspects. Pareto optimal buildings are identified, minimizing total life cycle environmental cost and operational environmental cost. Insulation levels, solar shading, and orientation are key factors in achieving optimal design. HVAC systems and electricity mixes also significantly influence optimal solutions. Lightweight and heavyweight buildings have distinct characteristics affecting heating and cooling demands. Variations in electricity mixes impact energy consumption and environmental costs of different HVAC system scenarios. The study emphasizes the need for a holistic life cycle approach and considering both operational and embodied impacts in building design. It underscores the importance of optimizing building characteristics while addressing climate change challenges. Further research should explore additional factors such as night cooling, HVAC system performance under climate change, and the inclusion of financial costs and visual comfort in the analysis.

## 1. Introduction

In 2019, buildings and the built environment were responsible for 38% of energy-related carbon dioxide (CO2) emissions and 35% of global energy consumption [1]. The manufacturing of building materials accounted for 26% of CO2 emissions related to the building sector, equivalent to 10% of total CO2 emissions, and 14% of global energy use in buildings, which corresponds to 5% of total energy consumption.

The impact of climate change on building performance has been widely recognized [2, 3]. Climate change affects various operational aspects of buildings (i.e. energy needs and thermal comfort performance), resulting in reduced heating demand and increased cooling demand [3–5]. The balance and change in operational emissions differ across regions due to factors such as system efficiencies, building design, and the carbon intensity of the electricity grid [3]. Cellura *et al* [6] show an increase in final energy demand for office buildings in southern Europe up to 120% by 2090. Chow and Levermore [7] find a reduction in final energy use for a well-insulated office building in Heathrow and Edinburgh (UK), while an increase is found for an office building from 1965. Blom *et al* [8] highlight the importance of system efficiency and energy sources for a Dutch case study. They reported higher environmental impacts if the building would implement a heat pump for space heating compared to having a gas boiler depending on the coefficient of performance. The latter effect is due to the higher environmental impact of electricity compared to natural gas in the Netherlands.

Existing policies predominantly emphasize the energy performance of buildings [9–11]. Consequently, greenhouse gas (GHG) emissions associated with the operational phase of buildings have significantly decreased from approximately 80% of life cycle building emissions to approximately 50%, confirmed by the analysis of 200+ buildings in the research of Röck *et al* [12]. Further, buildings with better energy performance, such as passive, low-energy, and near/zero energy buildings, were found to exhibit a higher relative and absolute contribution of embodied GHG emissions [12]. Hence, for these buildings, the embodied emissions are as significant as the operational emissions. Life cycle assessment (LCA) is a widely employed methodology to quantitatively evaluate the environmental impact of buildings throughout their life cycle, encompassing both embodied and operational emissions.

Early design decisions play a critical role in determining the final energy performance of buildings [13–15]. These decisions encompass factors such as building layout, orientation, building envelope, glazing surfaces, and thermal mass. Achieving an optimal balance between reducing heat losses during winter, dissipating excess heat during summer, and maximizing heat gains, while considering the influence of climate change, is of utmost importance [16].

The existing body of literature concerning building optimization primarily focusses on operational performance and its related GHG emissions [12, 17]. In cases where studies primarily emphasize the assessment of a building's embodied impact, they often narrow their focus to specific life cycle stages [17]. In cases where the whole life cycle is considered, the influence of climate change or changing energy mixes is mostly overlooked in line with the current European standard EN 15 804 [18] and EN 15 978 [19]. Both Roux *et al* [20] and Ramon and Allacker [21] showed the influence of climate change and energy mixes on the environmental impact of a limited number of case studies, with changing energy mixes being more crucial compared to climate change. These aspects should therefore also be integrated in whole life cycle building optimization studies. Furthermore, much of the research in this field tends to concentrate on existing buildings or neighborhoods (e.g [6, 22, 23]) wherein certain parameters, such as orientation or thermal mass, are already predetermined and thus not subject to optimization considerations.

This study aims to investigate the optimal building solutions from a holistic point of view within the context of climate change, examining the effects of different building characteristics on both the embodied and operational environmental impact. This paper aims to answer the following research questions: (1) how do various building characteristics influence the environmental impact of a building in the face of climate change, while considering thermal comfort requirements?; (2) to what extent do the contributions of embodied and operational emissions influence the optimal design of buildings?

This research focuses on office buildings in the Belgian context. These buildings are vulnerable to overheating, especially in the face of changing climates, owing to their substantial internal heat gains, often coinciding with peak solar gains, and high window-to-wall ratios (WWR), which exacerbate overheating risks [7, 24, 25]. Also, overheating in office environments negatively impacts employee productivity [26, 27]. Last, non-residential buildings in Europe consume 40% more energy than residential counterparts [28], with office buildings displaying greater variability in primary energy consumption for space conditioning, as evidenced by Moazami *et al* [23].

This research advances our understanding of sustainable building design in the context of climate change. By analyzing various building characteristics and their impact on both embodied and operational environmental costs, the study sheds light on the complex interplay of factors influencing the environmental performance of buildings. It gives insights in building design solutions minimizing both operational and embodied environmental costs as well as insights to improve both when certain parameters might already be fixed.

## 2. Methodology

In the following sections, the different aspects of the methodology (illustrated in figure 1) are discussed. The assessment flow to investigate building design solutions consists of a parametric LCA study including the use of a dynamic building energy simulation (further abbreviated as BES). Optimal building strategies are

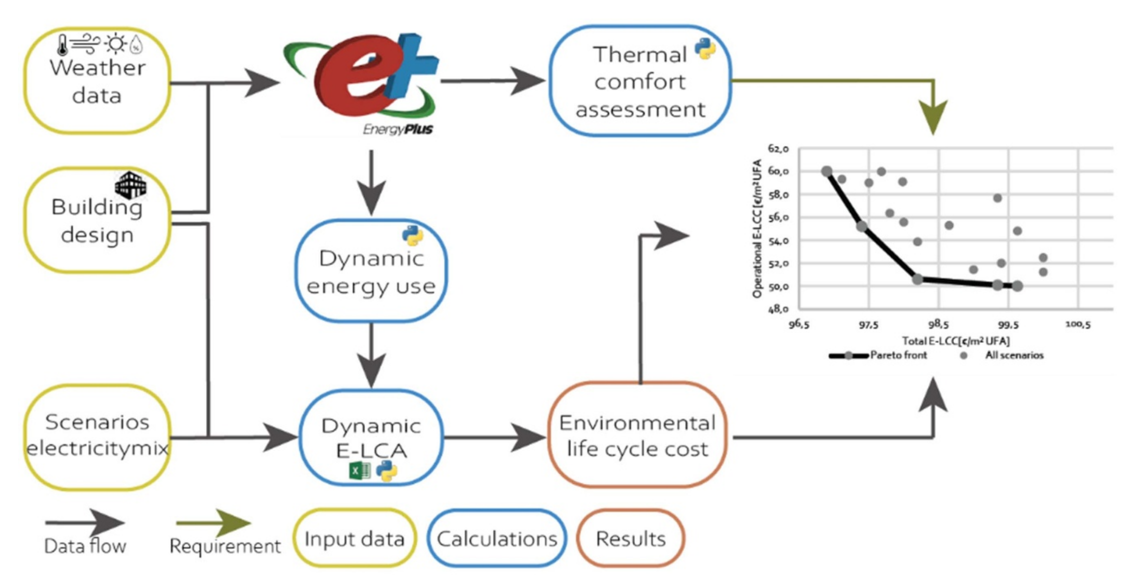


**Figure 1.** Assessment flow methodology.

selected based on a Pareto front. A medium-sized office building with beam typology has been used as case study.

### 2.1. Parametric variables

The influence of ten parameters is evaluated. An overview of the parameter values is provided in figure 2 and table 1.

Two **orientations** are evaluated: north–south and east–west.

Two variants of the **building layout** are assessed: cell offices and landscape offices (figure 3). The latter also provides a limited number of cell spaces and meeting rooms in line with the guidelines of the Flemish government [29]. Dimensions of the rooms are based on Neufert and Neufert [30] and Parys [31].

Three scenarios for the **floor-to-ceiling height** are defined based on the 'Kantoor 2000' study [32]: average (2.8 m), minimum (2.5 m), and maximum (3.4 m).

A heavy- and lightweight scenario are considered for the **thermal mass** of the building by implementing a massive concrete and timber building structure, respectively. An overview of the element build-ups of the external walls, walls between the different office zones, and the floors can be found in figure 4.

Regarding the **insulation level**, four scenarios are implemented for opaque elements in line with different energy standards through time: EPB 2006, NZEB 2022, passive minimum $U$ max-value, and passive maximum $U$ max-value, resulting in the following $U$-values: 0.6 W m$^{-2}$ K$^{-1}$, 0.24 W m$^{-2}$ K$^{-1}$, 0.15 W m$^{-2}$ K$^{-1}$, and 0.08 W m$^{-2}$ K$^{-1}$ respectively. Four additional scenarios are provided for window glazing insulation: double glazing, double glazing with sun-blocking, highly efficient (Table 1 provides an overview of the glazing characteristics).

Four **airtightness levels** are defined based on EPBD categories in the Belgian context [33]: bad, average, good, and very good, with corresponding v50-values of 12, 6, 3, and 1 m$^3$ hm$^{-2}$ respectively. The bad scenario represents the default one in the EPBD calculations, while the average and good scenario are in line with realistic expectations for new buildings. Achieving a value of 1 m$^3$ hm$^{-2}$ (very good) requires extensive expertise and care during execution and might increase construction costs.

For the **Window-to-Wall ratio** (WWR), three scenarios are implemented ranging from 20% to 40%, to 80% representing the range of WWR which can be found in Belgian office buildings 'Kantoor 2000' study [32].

Three scenarios for **solar shading** are investigated in line with current practice for office buildings: no shading, fixed shading with horizontal blades, and controlled shading with adjustable blade rotation based on solar radiation and zone temperature. The controlled shading system starts from the fixed shading system but allows a rotation of the blades between 0° (i.e. closed), 45° or 90° (i.e. horizontal). If the solar radiation is higher than 150 W m$^{-2}$, the zone temperature is higher than 24 °C, a rotation angle of 45° is used or 0° if no occupants are present. In other situations, the blades are set under an angle of 90 °C.

Last, different **HVAC systems,** shown in table 2 are considered. Based on Verbanck [34], five systems have been selected varying in production unit for heating and cooling as well as their emission systems.

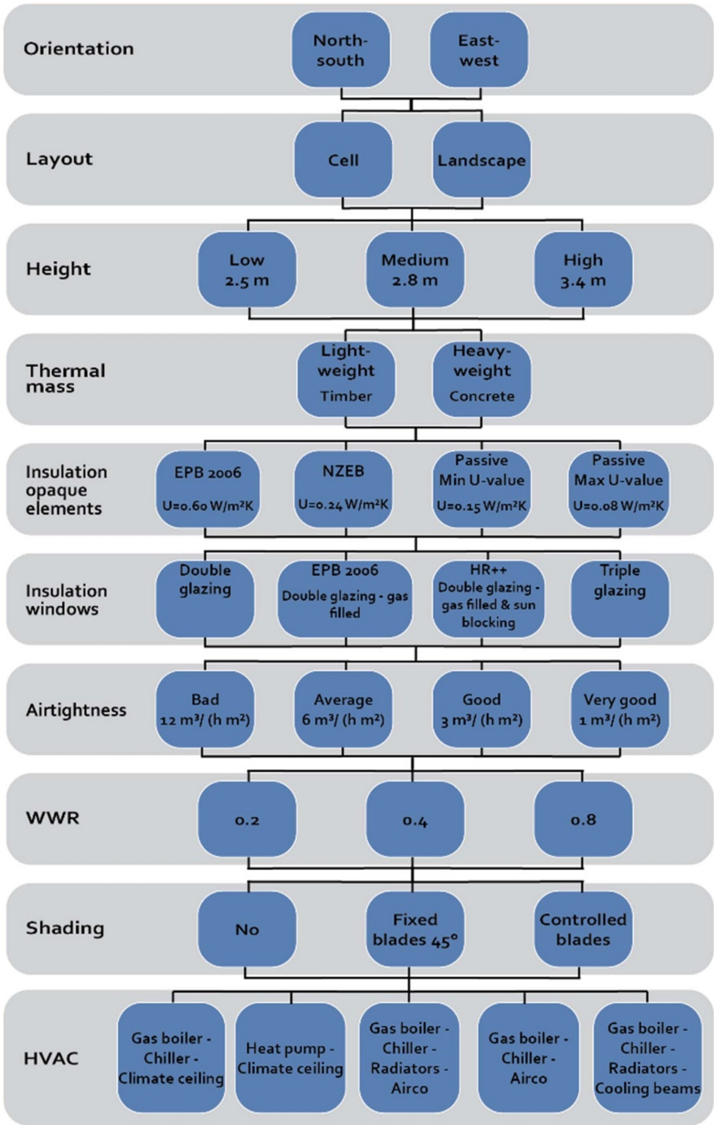


**Figure 2.** Flowchart parametric analysis.

**Table 1.** Overview characteristics different glazing types.

| Scenario | Ug-value [W m$^{-2}$ K$^{-1}$] | τ-value [−] | g-value [−] |
|---|---|---|---|
| Double glazing (double) | 2.9 | 0.81 | 0.77 |
| EPB standard 2006—double glazing gas filled (HR+) | 1.6 | 0.82 | 0.64 |
| Double glazing—gas filled & sun blocking (HR++) | 1.1 | 0.80 | 0.62 |
| Highly efficient triple glazing (Triple) | 0.6 | 0.70 | 0.50 |

In total this results in 34 560 possible combinations per layout scenario. However, some combinations are unlikely to occur (i.e. bad infiltration rate or double glazing with passive insulation scenarios; very good infiltration rate combined with EPB 2006 insulation scenario) and are therefore excluded to reduce the number of simulations to 24 840 simulations per layout scenario.

### 2.2. Building energy model

EnergyPlus v9.5 has been used for the dynamic BES. A multi-zone approach has been chosen, according to the layout description in section 2.1 and figure 3. For each zone, internal gains, ventilation and heating and cooling are provided as described in the subsequent paragraphs.

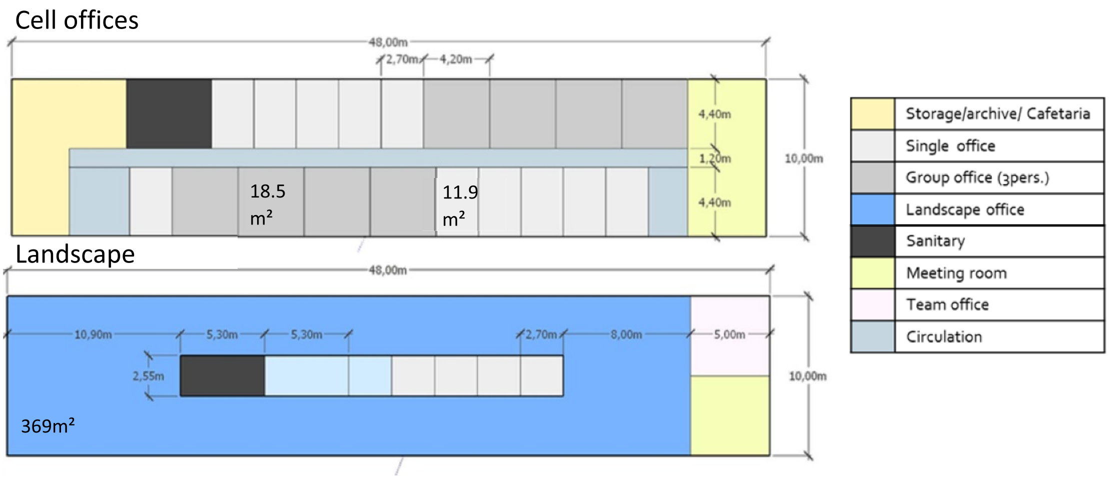


**Figure 3.** Building layout scenarios.

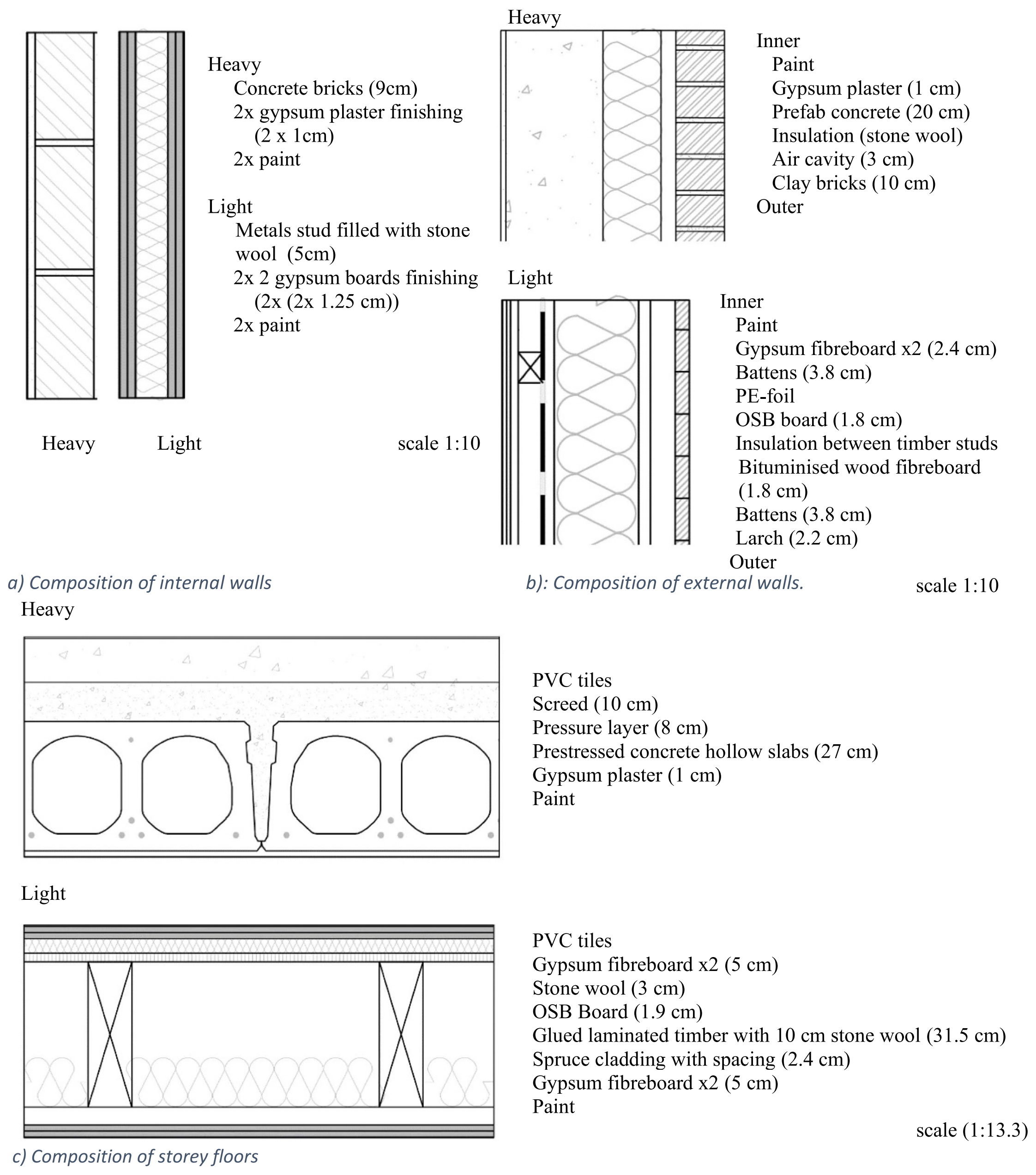


**Figure 4.** Composition building elements for heavyweight and lightweight thermal mass scenarios.

**Table 2.** Overview of HVAC system scenarios providing information about production and emission units including distribution fluid.

| | Production | | Emission (distribution) | |
|---|---|---|---|---|
| Abbreviation scenario | Heating | Cooling | Heating | Cooling |
| Bo_Ch_Cl_Cl | Condensing gas boiler | Chiller | Climate ceiling (water) | |
| He_He_Cl_Cl | Heat pump | | Climate ceiling (water) | |
| Bo_Ch_Ra_Ai | Condensing gas boiler | Chiller | Radiators (water) | Air-conditioning (air) |
| Bo_Ch_Ai_Ai | Condensing gas boiler | Chiller | Air-conditioning (air) | |
| Bo_Ch_Ra_Cb | Condensing gas boiler | Chiller | Radiators (water) | Cooling beams (water) |

Schedules for internal gains related to people, lighting, electric equipment are in line with EN 16798–1:2019 and EN 16798–2:2019 [35, 36]. Occupancy assumptions were made for different office types, with one person for cell offices (11.9 $m^2$ average size), three persons for group offices (18.5 $m^2$ average size), 15 $m^2$/person for landscape offices, 2 $m^2$/person for meeting rooms, and 1.5 $m^2$/person for the cafeteria. Illuminance levels of 500 lux for offices, 100 lux for the circulation hall, and 200 lux for the cafeteria are assumed. LED lighting efficacy was assumed at 150 lumen per watt based on recent data [37]. A lighting power of 5.33 W $m^{-2}$ for office spaces is obtained. The visible and convective fractions were set at 40% and 60% respectively (Efficiency of LEDs: The highest luminous efficacy of a white LED—DIAL, n.d.). Electric equipment was assumed to have a power of 12 W $m^{-2}$ with a radiant fraction of 20% [35].

The ventilation rate is determined based on EN 16798–1 [35]. A ventilation rate of 40 $m^3$ per hour per person was used to meet air quality requirements and CO2 concentration limits as recommended by 'Codex welfare at work' and in the context of Covid-19 [38]. The ventilation approach involved supplying untreated outside air to each zone and treating it to appropriate temperatures (i.e. 18 °C between October and March and 19 °C between April and September) using an ideal loads air system. Infiltration was considered based on the building's envelope leakage at 50 Pa, with a value of 0.04 used in accordance with EPBD regulations in Belgium [33].

The ideal loads air system objects simplified the space heating and cooling systems, controlling comfort based on operative temperatures. Heating/cooling setpoint temperatures are set at 21 °C/24 °C in line with in EN 167981–1 for office spaces with a mechanical cooling system (CEN, 2019) with a setback temperature of 16 °C/29 °C respectively. Unlimited heating and cooling capacities were assumed. Default assumptions for input parameters of the ZoneHVAC: IdealLoadsAirSystem object were used and are presented in Text S1 of the supplementary information. The net energy demands obtained from the BES serve as an input for the assessment of the operational energy in the building LCA, discussed in section 2.4.

Three solar shading systems were modeled using WindowShadingControl and WindowMaterial:Blind objects, controlled by the EnergyManagementSystem. The slat angle was adjusted based on indoor temperature, solar irradiation, and occupancy.

The BES components underwent thorough verification and were supported by similar studies. An overview can be found in Text S2 of the supplementary information.

### 2.3. Dynamic operational energy use

To assess climate change impact on the building's operational performance, the BES discussed in section 2.2 is run with two Typical Downscaled Years (TDY), representing average climate conditions [39]. These TDYs are extracted from the bias-corrected EC-Earth-driven convection-permitting climate model [40, 41] for both the recent past (i.e. 1975–2005) [42] and end-of-century (i.e. 2070–2100, further referred to as EoC) climate [43]. The latter considers an RCP 8.5 climate change scenario. The climate model has a spatial resolution of 2.8 km, includes the TERRA_URB [44, 45] to include effects of urban physics and provides hourly data. The location of Uccle in Belgium (50.80° N 4.36° E) is chosen, consistent with EPBD calculations for Belgian buildings.

In line with [41], a dynamic approach is implemented for estimating the operational energy use over the 60 years service life of the building assuming a yearly evolution of outdoor climatic conditions assuming an exponential growth rate. The latter is in line with the expected development of the outdoor temperature under the RCP 8.5 climate change scenario [2]. For each set of parametric variables, the BES is run for both the recent-past and EoC weather file. From the BES, the net demands for heating and cooling are obtained. A simplified calculation approach based on the Belgian EPN-calculation method [46] is employed to estimate the final energy demands for the different HVAC systems. The method multiplies the net demands for heating and cooling by default efficiencies of the HVAC subsystems. Although the part load ratio influences heating system efficiencies, its effect on annual energy use is limited ($<$10%) [47] and allows this simplified approach. The formulas of the EPN-method, including different assumptions for the different HVAC systems can be found in Text S3 and S4 of the supplementary information. These energy uses will be used as an input for the B6 phase in the building LCA described in the next section.

### 2.4. Building LCA

This study employs the Belgian LCA tool for buildings, Tool to Optimize the Total Environmental impact of Materials (TOTEM) version 2.2 [48]. TOTEM utilizes the MMG ('Environmental profile of building elements') LCA method [49], tailored to the Belgian context and aligned with the European standard EN 15 978 [19]. The functional unit in MMG is defined as one square meter useful floor area (further abbreviated as UFA) of a building assuming a service life of 60 years. Within this study, the building design options are evaluated between 2020 (year 0) and 2080 (year 60).

The MMG LCA method assesses 17 environmental impact indicators. At the time of developing the method, the first seven indicators were in line with European standards, EN 15804 + A1 [18] and EN 15 978 [19] and are therefore referred to as CEN indicators. The other ten indicators were added at the request of the regional authorities in Belgium and are based on the international reference life cycle data system handbook [50].

The MMG LCA method not only characterizes impact values (e.g. kg CO2 equivalent for GWP) but also allows for calculating an aggregated environmental score in monetary values (Euro) [51]. This monetization process multiplies the characterized impact values by a monetary value per indicator, determined through either the damage cost approach (potential cost caused by emissions) or the prevention cost approach (cost of avoiding environmental impacts) as described in De Nocker and Debacker [51]. The resulting costs represent external environmental costs, reflecting the transferred environmental damage to society. Central monetary values for Western Europe, consistent with TOTEM, are used in this study [51]. The results are typically presented for CEN, CEN+, and All indicators.

For the life cycle inventory (LCI), this study utilizes the Swiss Ecoinvent database version 3.3 [52], in line with TOTEM version 2.2, except for the energy sources. For the latter, Ecoinvent version 3.6 is used to include more up-to-date data regarding electricity mix compositions. Material production employs representative processes from Western Europe [49]. When Western Europe processes are unavailable, energy, transport, and water-related flows in the production processes (limited to the analyzed product, excluding underlying market processes) are substituted with available European mix processes [49]. Energy consumption during the construction stage, such as blowing cellulose, uses the Belgian electricity mix. Adaptations are made to the Ecoinvent datasets for certain products (e.g. timber, concrete, and natural stone) to align with Belgian practices [49]. Detailed information on these adaptations can be found in [49].

The building assessment follows the European standard EN 15 978 [19] and covers the before-use, use, and end-of-life (EOL) stages. The before-use stage includes production (A1–3) and construction process (A4–5), encompassing raw material extraction, transport, manufacturing, and building activities. The use stage includes maintenance (B2), component replacement (B4), operational energy use (B6), and operational water use (B7). The EOL stage encompasses deconstruction and demolition (C1), transport of construction and demolition waste (C2), waste processing (C3), and waste disposal (C4). Detailed scenarios for each stage can be found in [41].

For electricity use in B6, next to the static scenario using the current Belgian electricity mix, two future scenarios defined in [21] are used. The two dynamic scenarios are the BAU and 1.5 °C Target scenarios. The BAU scenario represents a worst-case scenario corresponding to minor climate change mitigation measures in line with the RCP 8.5 climate change scenario. On the contrary, the 1.5 °C Target scenario aligns with the 1.5 °C targets set in the Paris Agreement. Depending on the scenario, data are available till 2040 or 2050. Due to uncertainties, the electricity mix is assumed constant from 2050 onwards. Detailed information about the scenarios and their mix evolution can be found in [21]. The energy uses for both gas and electricity are based on the methodology described in section 2.3.

The parameter study's full LCI can be found in supplementary information B.1.

### 2.5. Pareto optimal buildings

Overall, 24 840 combinations per layout are evaluated for each electricity mix scenario resulting in 74 520 evaluated building options. A full enumeration of all possible scenarios has been performed.

Pareto optimal buildings are defined as the most preferred options minimizing the total environmental life cycle cost (E-LCC) and the operational E-LCC, both expressed per m$^2$ UFA. Figure 5 illustrates the identification of Pareto optimal solutions schematically. In line with [53], an 'absolute optimum' and a 'sub-optimum' are defined. The absolute optimum (indicated with *A* in figure 5) is the scenario with the

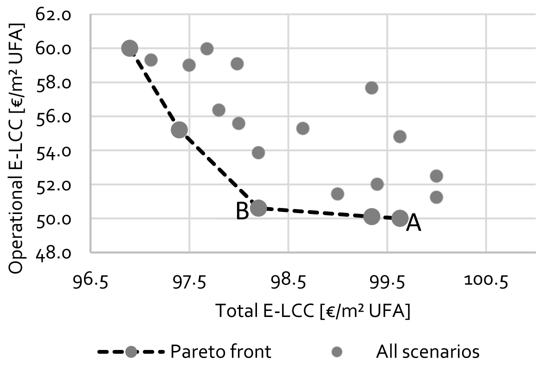


**Figure 5.** Illustration of identification of Pareto optimal scenarios (big dots) along the Pareto front (dashed line). Definition of 'absolute minimum' (A) and 'sub-optimum' (B) for a typical Pareto front.

lowest operational E-LCC. However, the results reveal that a high additional total E-LCC is required to reach point *A* from point *B* while only a slight reduction on the *y*-axis is achieved (i.e. point *A* is on the non-steep part of the Pareto front). Therefore, a sub-optimum was defined in [53], shown in point *B* in figure 5. This point might be preferred compared to point *A* as it requires a lower total E-LCC, while the operational E-LCC gain is approximately the same.

## 3. Results

In this results section, first the outcomes for the cell layout scenarios are discussed as in architectural practice this decision is often taken at the beginning of the design process rather than being a parameter subject to optimization throughout the course of the project. Furthermore, our initial focus is directed towards two HVAC scenarios: the Bo_Ch_Cl_Cl scenario, having a condensing gas boiler as heat production, chiller for space cooling and using a climate ceiling to provide space heating and cooling to all rooms; and the He_He_Cl_Cl scenario, representing a fully electric building with a reservisble heat pump combined with a climate ceiling.

The structure of this results section is as follows: firstly, the influence of building characteristics is shown, followed by the identification of Pareto optimal building solutions and an analysis of the embodied versus operational share. Next, the influence of electricity mixes is explored. Subsequently, variations across different HVAC systems are analyzed before concluding with a final section that expands upon the distinctions in outcomes related to landscape layouts.

### 3.1. Building characteristics

The analysis reveals a clear categorization by the WWR into three distinct clusters. These clusters demonstrate a consistent upward trend in both operational and total E-LCC as WWR increases, as illustrated in figure 6. The increase in total E-LCC with increasing WWR is higher compared to the increase in operational E-LCC.

Further, the solar shading scenarios divide the results in two clusters (figure 7). The absence of solar shading leads to lower E-LCC values but, simultaneously, results in higher operational E-LCC compared to scenarios incorporating solar shading strategies. In addition, scenarios implementing fixed solar shading show slightly higher operational E-LCC in contrast to controlled solar shading approaches. This difference in operational E-LCC is more pronounced in instances of higher WWR, especially within the context of fully electric buildings, where cooling has an equal importance as heating for the operational E-LCC. Consequently, for full electric buildings, reducing both heating and cooling needs becomes more important.

Lightweight scenarios are associated with higher operational E-LCC. However, as WWR increases, the E-LCC rises and surpasses that of its heavyweight counterpart (see figure 8).

Building orientation plays a crucial role in determining operational E-LCC. North–south oriented buildings tend to yield lower operational E-LCC values, resulting in lower total E-LCC, as illustrated in figure 9. The difference between both orientations becomes more pronounced with increasing WWR and the absence of solar shading.

The building insulation level, being a result of the scenarios for window insulation and opaque insulation levels significantly impacts the operational E-LCC. Window insulation shows increasing variations among its scenarios as WWR increases (figure 10). At the same time, the insulation level of opaque elements exerts influence on both operational and total E-LCC (figure 11), with notable overlaps for passive *U*-values.

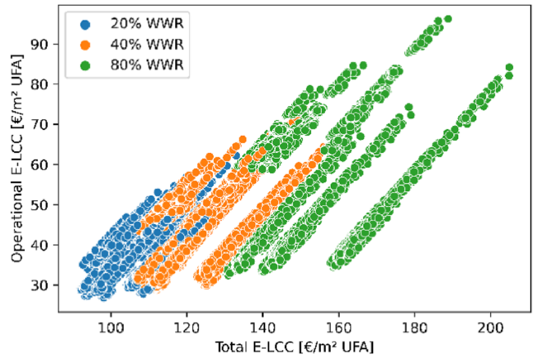


**Figure 6.** E-LCC compared to operational E-LCC for cell layout buildings distinguishing different WWR for the Bo_Ch_Cl_Cl and He_He_Cl_Cl HVAC scenarios with BAU electricity mix.

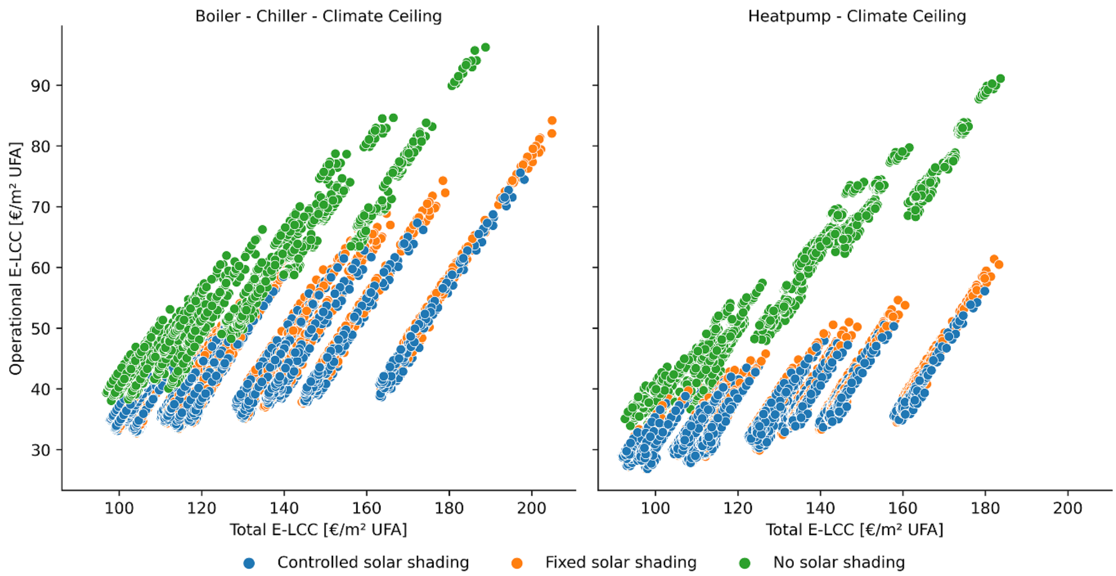


**Figure 7.** E-LCC compared to operational E-LCC for cell layout buildings distinguishing different solar shading scenarios for the Bo_Ch_Cl_Cl (left) and He_He_Cl_Cl (right) HVAC scenarios with BAU electricity mix.

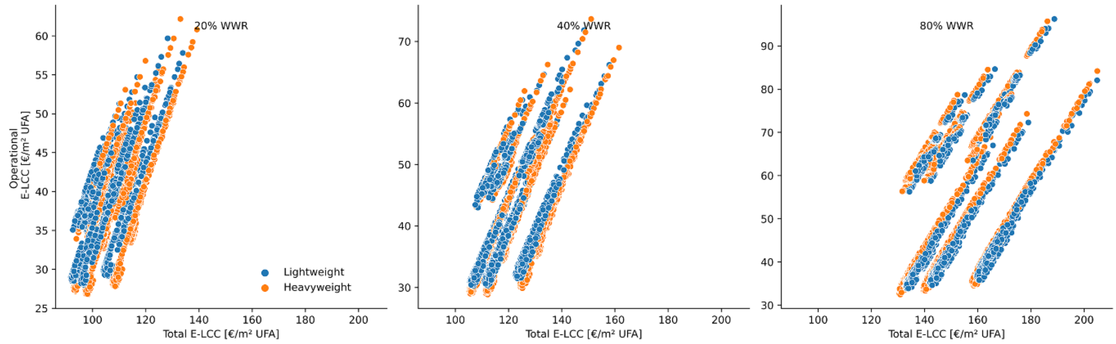


**Figure 8.** E-LCC compared to operational E-LCC for cell layout buildings distinguishing lightweight and heavyweight building scenarios for the Bo_Ch_Cl_Cl and He_He_Cl_Cl HVAC scenarios with BAU electricity mix. Results are showed from left to right for 20%, 40% and 80% WWR.

Notably, a wider spectrum of results is observed for Bo_Ch_Cl_Cl compared to fully electric buildings, suggesting a potential link to increased heating requirements.

Last, airtightness, appears to exhibit more scattered effects across the scenarios, suggesting that its influence may be comparatively less pronounced when juxtaposed with other studied parameters.

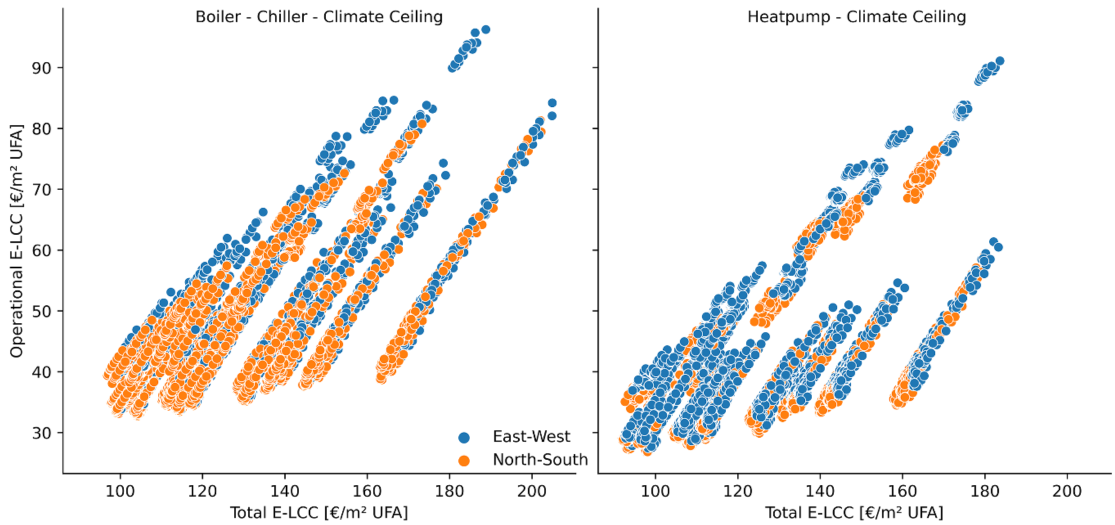


**Figure 9.** Total E-LCC compared to operational E-LCC for cell layout buildings distinguishing north–south and east–west orientations for the Bo_Ch_Cl_Cl (Upper) and He_He_Cl_Cl (bottom) HVAC scenarios with BAU electricity mix.

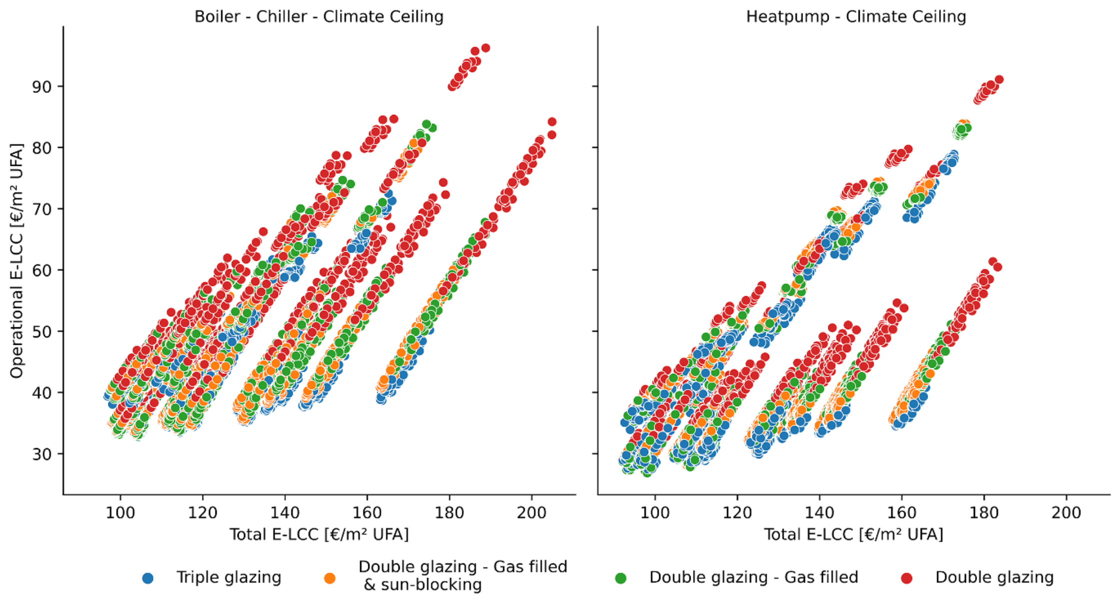


**Figure 10.** E-LCC compared to operational E-LCC for cell layout buildings distinguishing window insulation levels for the Bo_Ch_Cl_Cl (upper) and He_He_Cl_Cl (bottom) HVAC scenarios with BAU electricity mix.

### 3.2. Pareto optimal buildings & influence operational vs embodied

For the Bo_Ch_Cl_Cl HVAC system and BAU electricity mix, table 3 shows that the Pareto optimal buildings are well-insulated, low-height buildings with a WWR of 20% and north–south oriented windows. Pareto buildings 6 and 7 presented in figure 12 are on the non-steep decline part of the Pareto front. These can hence be questioned and are less interesting. Pareto optimum 5 is identified as a sub-optimum. If only the operational impact would be optimized, lightweight buildings would not be preferred.

In figure 12, the contribution of different building elements and operational energy use to the building's E-LCC is shown. Although the total E-LCC does not differ much, the share operational—embodied evolves from 40%–60% to 30%–70% across the different Pareto optima.

Pareto optimum 1 has a higher share for electricity use (linked to cooling), as shown in figure 12, due to the absence of solar shading, but the total E-LCC is still the lowest due to this absence. Pareto building 2 has a 0.9% higher E-LCC compared to building 1, but operational energy cost decreases by 11.4%. Pareto buildings 3 and 4 have limited reduction in operational E-LCC and a slight increase in total E-LCC.

Figure 12 also highlights a shift in contributions between Pareto buildings 4 and 5. The first four buildings are lightweight structures with a higher impact on the storey floor, while the last three buildings

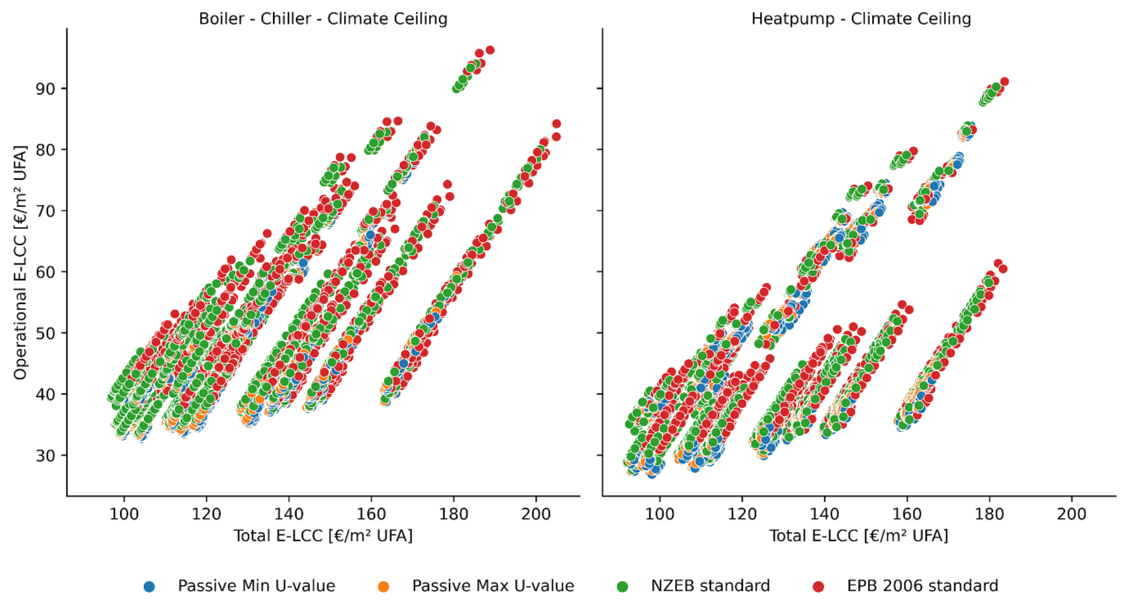


**Figure 11.** E-LCC compared to operational E-LCC for cell layout buildings distinguishing different insulation levels for opaque elements for the Bo_Ch_Cl_Cl (Upper) and He_He_Cl_Cl (bottom) HVAC scenarios with BAU electricity mix.

**Table 3.** Overview building characteristics Pareto optimal cell layout buildings with Bo_Ch_Cl_Cl HVAC system for different electricity mix scenarios, minimizing the E-LCC and operational E-LCC. Sub-optimum underlined, less interesting buildings in italic. All optima have a WWR of 20% and north–south oriented windows.

| Electricity scenario | Pareto | Thermal mass | Insulation level ext. walls | Insulation level windows | Air-tightness | Height | Solar shading | E-LCC B6 [€/m$^2$] | E-LCC full [€/m$^2$] |
|---|---|---|---|---|---|---|---|---|---|
| BAU | Par. 1 | Light | NZEB | Triple | Average | Low | No | 39.4 | 96.9 |
| | Par. 2 | Light | NZEB | HR++ | Very good | Low | Controlled | 34.9 | 97.8 |
| | Par. 3 | Light | NZEB | Triple | Very good | Low | Controlled | 34.6 | 97.9 |
| | Par. 4 | Light | Passive max $U$ | Triple | Good | Low | Fixed | 34.4 | 98.0 |
| | Par. 5 | Heavy | Passive max $U$ | HR±± | Very good | Low | Fixed | 33.3 | 98.8 |
| | *Par. 6* | *Heavy* | *Passive max U* | *Triple* | *Average* | *Low* | *Fixed* | *33.1* | *99.0* |
| | *Par. 7* | *Heavy* | *Passive min U* | *Triple* | *Average* | *Average* | *Fixed* | *32.7* | *104.2* |
| Static | Par. 1 | Light | NZEB | Triple | Good | Low | No | 36.1 | 93.7 |
| | Par. 2 | Light | NZEB | Triple | Very good | Low | Controlled | 32.5 | 95.8 |
| | Par. 3 | Light | Passive max $U$ | Triple | Very good | Low | Fixed | 32.4 | 95.9 |
| | Par. 4 | Heavy | Passive max $U$ | HR±± | Very good | Low | Fixed | 31.3 | 96.9 |
| | *Par. 5* | *Heavy* | *Passive max U* | *Triple* | *Average* | *Low* | *Fixed* | *31.2* | *97.2* |
| | *Par. 6* | *Heavy* | *Passive min U* | *Triple* | *Average* | *Average* | *Fixed* | *30.9* | *102.4* |
| 1.5 °C Target | Par. 1 | Light | NZEB | Triple | Good | Low | No | 34.2 | 91.7 |
| | Par. 2 | Light | Passive Max U | Triple | Very good | Low | Fixed | 31.1 | 94.7 |
| | *Par. 3* | *Heavy* | *Passive max U* | *HR++* | *Very good* | *Low* | *Fixed* | *30.2* | *95.7* |
| | *Par. 4* | *Heavy* | *Passive max U* | *Triple* | *Average* | *Low* | *Fixed* | *30.1* | *96.1* |
| | *Par. 5* | *Heavy* | *Passive min U* | *Triple* | *Average* | *Average* | *Fixed* | *29.9* | *101.4* |

Abbreviations & terms used: E-LCC B6: Operational E-LCC; NZEB: $U = 0.24$ W m$^2$K$^{-1}$; Passive Max $U$: $U = 0.15$ W m$^2$ K$^{-1}$; Passive Min $U$: $U = 0.08$ W m$^2$ K$^{-1}$; HR++: Double glazing with $Ug = 1.1$ W m$^2$K$^{-1}$; Triple: Triple glazing with $Ug$ of 0. W m$^2$ K$^{-1}$; ext.: external, Contr.: controlled, Par.: Pareto.

show a reduction in storey floor contribution but an increase in external wall contribution. The decrease in operational energy use for Pareto 4 cannot compensate for the increase in embodied impacts of heavyweight buildings, resulting in higher E-LCC. Pareto 7 has the highest embodied impact due to the higher floor-to-ceiling height.

For the non-Pareto optimal buildings, higher WWRs lead to higher environmental impacts as shown in figure 6. The latter is caused by a higher embodied environmental cost per m$^2$ window area compared to a m$^2$ external wall area. Further, buildings without solar shading may have comparable E-LCC to buildings with solar shading (see figure 7), but the share of environmental cost related to operational energy use is

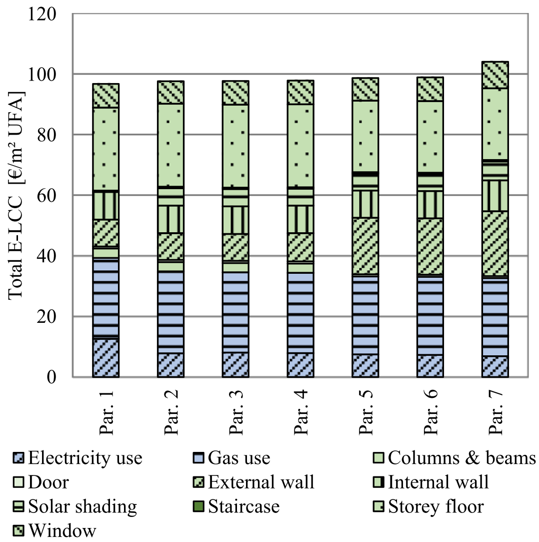


**Figure 12.** Environmental life cycle cost for the different element categories and energy services for the different Pareto optimal buildings with Bo_Ch_Cl_Cl HVAC system and BAU electricity mix. Embodied impacts are indicated in green while operational impacts (electricity use) are indicated in blue.

higher. Similar trends can be observed for the insulation level of opaque elements (figure 11) and windows (figure 10).

Similar as to the Bo_Ch_Cl_Cl scenario and BAU electricity mix, the sub-optimal building scenario for the He_He_Cl_Cl HVAC system is an airtight, heavyweight, low-height building with a WWR of 20% and north–south oriented windows, as shown in table 4. The insulation level for opaque elements is identical while the windows have a lower insulation level. Pareto buildings 5 and 6 are on the non-steep decline part of the Pareto front. These can hence be questioned and are less interesting.

For the He_He_Cl_Cl HVAC system, the share operational—embodied, shown in figure 13, only slightly differs across the different Pareto optimal scenarios remaining around 30%–70%. For this HVAC system, all Pareto optimal scenarios have solar shading to reduce the cooling demand. The efficiency of the heat pump increases the importance of cooling, making solutions with lower cooling demands preferred. Pareto 6 shows that improved insulation level only slightly reduces the operational E-LCC and is outweighed by the increase in embodied E-LCC.

### 3.3. Influence electricity mixes

The electricity mix scenario substantially influences the position of the Pareto front, as illustrated in figure 14, with decreasing operational E-LCC moving from the BAU to Static to 1.5 °C Target scenario in line with the decreasing cost of the respective scenarios.

For buildings with a heat pump (He_He_Cl_Cl), an additional Pareto optimal building without solar shading is identified for the Static and 1.5 °C Target scenarios (see table 4). However, these buildings are not Pareto optimal for the BAU electricity mix due to the increasing environmental cost of the electricity mix in the future. The position of the sub-optimum also changes with variations in the environmental cost of the electricity mix, reducing the number of interesting Pareto optima. The Pareto optima on the non-steep part of the front are buildings with high thermal insulation levels which lead to minimal operational E-LCC. However, only minimizing the latter, would increase the embodied E-LCC, which stresses the importance of a whole life cycle approach.

For the Bo_Ch_Cl_Cl scenario, the buildings with the lowest total E-LCC across the different electricity mix scenarios, have no solar shading (see table 3). For the BAU scenario, a building with an average airtightness level comes forward reducing the energy use for cooling compared to buildings with good airtightness levels.

As the environmental impact of the electricity mix decreases (from BAU to Static, to 1.5 °C Target scenario), fewer building variants are found on the Pareto front. The sub-optimum also changes, resulting in a decrease in the number of interesting Pareto buildings due to the decreasing trend in environmental cost of the electricity mix scenarios.

**Table 4.** Overview building characteristics Pareto optimal cell layout buildings with He_He_Cl_Cl HVAC system for different electricity mix scenarios, minimizing the total E-LCC and operational E-LCC. Sub-optimum underlined, less interesting buildings in italic. All optima have a WWR of 20% and north–south oriented windows.

| Elec. scenario | Pareto | Thermal mass | Insulation level ext. walls | Insulation level windows | Air-tightness | Height | Solar shading | E-LCC B6 [€/m$^2$] | E-LCC full [€/m$^2$] |
|---|---|---|---|---|---|---|---|---|---|
| BAU | Par. 1 | Light | NZEB | HR++ | Very Good | Low | Fixed | 29.0 | 91.7 |
| | Par. 2 | Light | NZEB | HR++ | Good | Low | Controlled | 28.9 | 91.8 |
| | Par. 3 | Light | NZEB | Triple | Very good | Low | Fixed | 28.8 | 91.9 |
| | Par. 4 | Heavy | Passive max U | HR± | Very good | Low | Fixed | 27.4 | 92.9 |
| | *Par. 5* | *Heavy* | *Passive min U* | *HR+* | *Average* | *Low* | Fixed | *27.2* | *93.6* |
| | *Par. 6* | *Heavy* | *Passive min U* | *Triple* | *Average* | *Average* | Fixed | *26.8* | *98.3* |
| Static | Par. 1 | Light | NZEB | Triple | Bad | Low | No | 26.1 | 83.6 |
| | Par. 2 | Light | NZEB | HR++ | Very good | Low | Fixed | 21.6 | 84.3 |
| | Par. 3 | Light | NZEB | HR++ | Good | Low | Controlled | 21.5 | 84.4 |
| | Par. 4 | Light | NZEB | Triple | Very good | Low | Fixed | 21.4 | 84.5 |
| | *Par. 5* | *Heavy* | *Passive max U* | *HR+* | *Very good* | *Low* | Fixed | *20.4* | *85.9* |
| | *Par. 6* | *Heavy* | *Passive min U* | *HR+* | *Average* | *Low* | Fixed | *20.2* | *86.6* |
| | *Par. 7* | *Heavy* | *Passive min U* | *Triple* | *Average* | *Average* | Fixed | *19.9* | *91.4* |
| 1.5 °C Target | Par. 1 | Light | NZEB | Triple | Bad | Low | No | 20.9 | 78.5 |
| | Par. 2 | Light | NZEB | HR±± | Very Good | Low | Fixed | 17.3 | 80.0 |
| | *Par. 3* | *Light* | *NZEB* | *HR++* | *Good* | *Low* | Controlled | *17.3* | *80.1* |
| | *Par. 4* | *Light* | *NZEB* | *Triple* | *Very good* | *Low* | Fixed | *17.2* | *80.3* |
| | *Par. 5* | *Heavy* | *Passive max U* | *HR+* | *Very good* | *Low* | Fixed | *16.3* | *81.9* |
| | *Par. 6* | *Heavy* | *Passive min U* | *HR+* | *Average* | *Low* | Fixed | *16.2* | *82.6* |
| | *Par. 7* | *Heavy* | *Passive min U* | *Triple* | *Average* | *Average* | Fixed | *16.0* | *87.5* |

Abbreviations & terms used: E-LCC B6: Operational E-LCC; NZEB: $U = 0.24$ W m$^2$K$^{-1}$; Passive Max *U*: $U = 0.15$ W m$^2$ K$^{-1}$; Passive Min *U*: $U = 0.08$ W m$^2$ K$^{-1}$; HR+: Double glazing with $Ug = 1.6$ W m$^2$ K$^{-1}$;HR++: Double glazing with $Ug = 1.1$ W m$^2$ K$^{-1}$; Triple: Triple glazing with $Ug$ of 0.6 W m$^2$ K$^{-1}$; ext.: external, Contr.: controlled, Par.: Pareto.

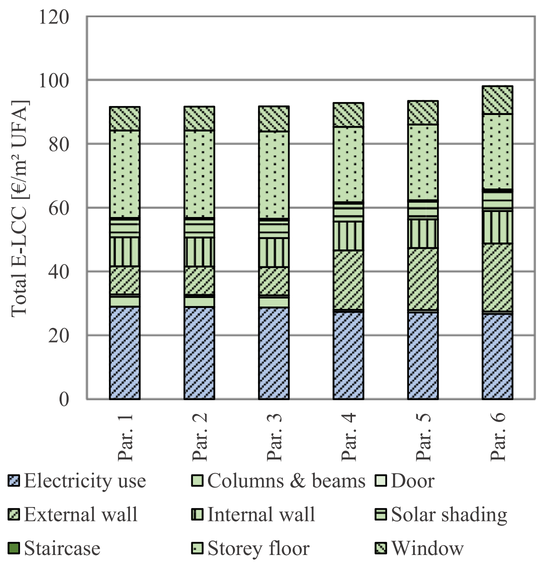


**Figure 13.** Environmental life cycle cost for the different element categories and energy services for the different Pareto optimal buildings with He_He_Cl_Cl HVAC system and BAU electricity mix. Embodied impacts are indicated in green while operational impacts (electricity use) are indicated in blue.

### 3.4. Influence HVAC systems

Similar trends as discussed before can be found for the other HVAC systems, though the Pareto optima differ. Figure 15 shows lower operation E-LCC for the system providing heating and cooling through a heat pump due to the higher system efficiency.

An overview of all Pareto optima and their characteristics can be found in tables S3 and S4 of the supplementary information. Although different Pareto optima are identified, all buildings have north–south

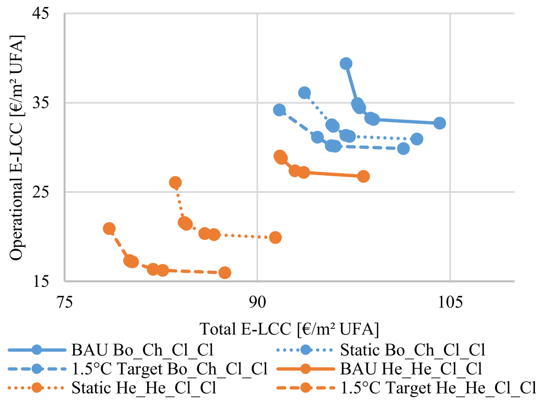


**Figure 14.** Pareto fronts for Bo_Ch_Cl_Cl and He_He_Cl_Cl HVAC scenarios for BAU, Static and 1.5 °C Target scenario.

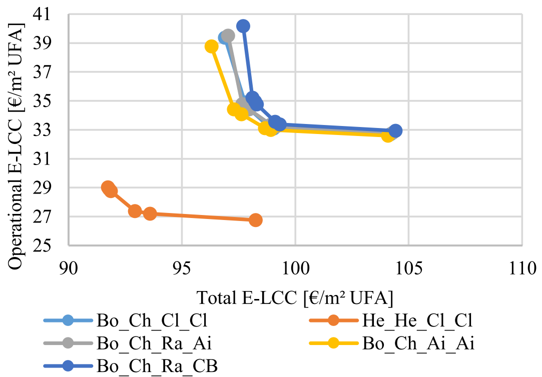


**Figure 15.** Pareto fronts different HVAC scenarios for BAU electricity mix scenario.

oriented windows, 20% WWR, low floor-to-ceiling height, and good insulation. The first part of the Pareto front consists of lightweight buildings, while the second part mainly includes heavyweight buildings.

Compared to buildings with a condensing gas boiler and chiller (Bo_Ch_Cl_Cl scenario), the building with a heat pump has lower insulation but includes solar shading to reduce cooling demand. The efficiency of the heat pump increases the importance of cooling, making solutions with lower cooling demands preferred.

Across the sub-optima, all have a heavyweight structure, except the Bo_Ch_Ai_Ai scenario. This system has higher efficiencies and lower end-uses, making a scenario with slightly higher operational energy use combined with a building with lower embodied impacts interesting.

### 3.5. Landscape layout

Fewer Pareto optimal buildings are identified for buildings with landscape layout. Appendix B.4 in supplementary material provides detailed results of all Pareto optimal buildings for different HVAC systems and electricity mixes. Still, all Pareto optimal buildings have a 20% WWR. Most of these buildings have external walls in line with the BEN standard, low floor-to-ceiling height, and poor airtightness level. The significance of cooling in the energy balance of these buildings is indicated by the importance of bad airtightness levels in the optima. Improving airtightness and incorporating free cooling could lead to better performance by reducing the demand for active cooling and heating. The landscape layout favors fewer lightweight buildings due to higher operational costs compared to heavyweight buildings.

In the BAU electricity mix and Bo_Ch_Cl_Cl HVAC scenario, all buildings on the Pareto front in the upper part of table 5 have a north–south orientation. As the environmental cost for the electricity mix decreases, the insulation level of the windows increases since gas end-uses become more important. Transitioning from the first to the second Pareto optimal building (from a lightweight building with glazing according to the EPB 2006 standard to a heavyweight building with double glazing and sun blocking) results in a 4.8% reduction in operational cost, with only a 0.2% increase in E-LCC.

For the 1.5 °C Target electricity mix, the first Pareto optimal building with higher cooling demands (east–west oriented windows and no solar shading) is favored due to the reduction in environmental cost for

**Table 5.** Overview building characteristics Pareto optimal landscape buildings with Bo_Ch_Cl_Cl HVAC scenario for different electricity mix scenarios. Sub-optimum underlined, less interesting buildings in italic. All scenarios have a WWR of 20%.

| Electricity scenario | Pareto | Thermal mass | Insulation level ext. walls | Insulation windows | Airtightness | Height | Orientation | Solar shading | E-LCC full [€/m$^2$] | E-LCC B6 [€/m$^2$] |
|---|---|---|---|---|---|---|---|---|---|---|
| BAU | Par. 1 | Light | NZEB | HR+ | Bad | Low | north–south | Fixed | 104.9 | 46.1 |
| | Par. 2 | Heavy | NZEB | HR++ | Bad | Low | north–south | Fixed | 105.1 | 43.9 |
| | Par. 3 | Heavy | NZEB | Triple | Bad | Low | north–south | Fixed | 105.3 | 43.6 |
| | *Par. 4* | *Heavy* | *Passive min U* | *HR+* | *Average* | *High* | *north–south* | *Fixed* | *117.8* | 42.8 |
| 1.5° Target | Par. 1 | Light | NZEB | HR+ | Bad | Low | east–west | No | 98.2 | 45.4 |
| | Par. 2 | Light | NZEB | HR+ | Bad | Low | north–south | Fixed | 98.9 | 40.1 |
| | Par. 3 | Heavy | NZEB | Triple | Bad | Low | north–south | Fixed | 100.0 | 38.4 |
| | Par. 4 | *Heavy* | *Passive min U* | *HR+* | *Average* | *High* | *north–south* | *Fixed* | *112.7* | *37.7* |
| Static | Par. 1 | Light | NZEB | HR+ | Bad | Low | north–south | Fixed | 101.1 | 42.3 |
| | Par. 2 | Heavy | NZEB | Triple | Bad | Low | north–south | Fixed | 102.0 | 40.3 |
| | *Par. 3* | *Heavy* | *Passive min U* | *HR+* | *Average* | *High* | *north–south* | *Fixed* | *114.5* | *39.6* |

Abbreviations & terms used: E-LCC B6: Operational E-LCC; NZEB: $U = 0.24$ W m$^2$ K$^{-1}$; Passive min *U*: $U = 0.08$ W m$^2$ K$^{-1}$; HR+: Double glazing with $Ug = 1.6$ W m$^2$ K$^{-1}$; HR++: Double glazing with $Ug = 1.1$ W m$^2$ K$^{-1}$; Triple: Triple glazing with $Ug$ of 0.6 W m$^2$ K$^{-1}$; ext.: external, Par.: Pareto.

**Table 6.** Overview building characteristics Pareto optimal landscape buildings with He_He_Cl_Cl HVAC scenario for different electricity mix scenarios. Sub-optimum underlined, less interesting buildings in italic. All scenarios have a WWR of 20% and north–south orientation.

| Elec. Scenario | Pareto | Thermal mass | Insulation level ext. walls | Insulation windows | Airtightness | Height | Solar shading | E-LCC full [€/m$^2$] | E-LCC B6 [€/m$^2$] |
|---|---|---|---|---|---|---|---|---|---|
| BAU | Par. 1 | Heavy | BEN stand. | HR±± | Bad | Low | Fixed | 99.6 | 38.3 |
| | *Par. 2* | *Heavy* | *Passive max U* | *HR+* | *Average* | *High* | *Fixed* | *111.3* | *37.4* |
| 1.5° Target | Par. 1 | Heavy | EPB stand. 2006 | Triple | Bad | Low | No | 83.3 | 28.0 |
| | Par. 2 | Light | BEN stand. | Double | Bad | Low | Fixed | 83.5 | 24.7 |
| | Par. 3 | Heavy | BEN stand. | HR±± | Bad | Low | Fixed | 84.1 | 22.9 |
| | Par. 4 | *Heavy* | *Passive max U* | *EPB 2006* | *Average* | *High* | *Fixed* | *96.2* | *22.3* |
| Static | Par. 1 | Light | BEN stand. | Double | Bad | Low | Fixed | 89.5 | 30.7 |
| | Par. 2 | Heavy | BEN stand. | HR±± | Bad | Low | Fixed | 89.7 | 28.5 |
| | *Par. 3* | *Heavy* | *Passive Max U* | *HR+* | *Average* | *High* | *Fixed* | *101.7* | *27.8* |

Abbreviations & terms used: E-LCC B6: Operational E-LCC; EPB 2006: $U = 0.6$ W m$^2$ K$^{-1}$; NZEB: $U = 0.24$ W m$^2$ K$^{-1}$; Passive max *U*: $U = 0.15$ W m$^2$ K$^{-1}$; HR+: Double glazing with $Ug = 1.6$ W m$^2$ K$^{-1}$; HR++: Double glazing with $Ug = 1.1$ W m$^2$ K$^{-1}$; Triple: Triple glazing with $Ug$ of 0.6 W m$^2$ K$^{-1}$; ext.: external, Par.: Pareto.

the electricity mix. Moving to the second Pareto optimal building (with reduced cooling demand) reduces the operational cost by 11.7% but increases the E-LCC by 0.7%. The subsequent Pareto optimal building reduces the operational cost by 4.3% while increasing the E-LCC by 1.1%.

In the He_He_Cl_Cl HVAC scenario, all Pareto optima, shown in table 6 have north–south oriented windows and a 20% WWR. Generally, these optima have lower insulation levels compared to the Bo_Ch_Cl_Cl HVAC scenario due to both heating and cooling being provided by electricity, with a greater emphasis on cooling. For the BAU electricity mix, the number of Pareto optima is reduced to two heavyweight buildings, of which only the first one is deemed interesting. In the 1.5 °C Target electricity mix, the first Pareto optimal building lacks solar shading due to the lower environmental cost for the electricity mix. Compared to the Bo_Ch_Cl_Cl HVAC scenario, the first optimum on the front for He_He_Cl_Cl features a heavyweight building with lower insulation for external walls and higher insulation for windows.

For HVAC scenarios with improved efficiency for the chiller or heat pump, there is no difference in Pareto optima among the different electricity mixes. However, the number of interesting scenarios may vary. Additionally, as cooling generation efficiency increases more than heating efficiency, more scenarios without solar shading are observed.

## 4. Discussion

The analysis of buildings with cell layout revealed minimal differences between lightweight and heavyweight constructions. Heavyweight buildings showed reduced cooling demands only in landscape layouts, suggesting a greater role of thermal mass in structures with a lower wall-to-floor area ratio. Efficient heat dissipation during nighttime is crucial for heavyweight buildings. Although night cooling was not considered in this analysis, significant differences in Pareto optimal buildings are unlikely. However, incorporating night cooling may result in slightly higher cooling demands, making heavyweight buildings more favorable compared to lightweight ones.

All Pareto optimal buildings have a significant share of environmental cost related to gas use, particularly for heating ventilation air. Heat recovery was not considered in this study, but it would reduce gas use similarly for all buildings without affecting the Pareto optima.

The largest differences in environmental cost were observed between buildings using gas for heating and those using electricity across various HVAC systems. However, the analysis is limited to the operational impact of the HVAC system and did not consider the embodied environmental costs. A simplified energy end-use estimation was used to prioritize building characteristics, while variations in heating and cooling performance throughout the year should be explored further. Incorporating environmental costs and detailed energy estimations is expected to amplify the contrast between heat pump and condensing gas boiler–chiller systems, consistent with Verbanck's findings [34] of higher environmental costs for the latter.

In this study, a full enumeration of all possible scenarios was still feasible. Though, it is recommended for future research to focus on gradient-based or metaheuristic optimization algorithms to allow for more detailed energy simulations and sizing of HVAC systems to include in the embodied environmental cost calculation. This would furthermore allow to include some parameters in a continuous way, such as WWR, which has now been descritized to three options.

Surprisingly, lightweight buildings without solar shading did not emerge as Pareto optimal solutions in terms of energy efficiency or cooling end-use. Identifying environmentally optimal building elements could lead to reduced environmental impact in heavyweight buildings, potentially making them more favorable than lightweight options. The same applies to lightweight building elements.

Utilizing the 1.5 °C Target electricity mix decreased environmental impact, offsetting slightly higher cooling energy consumption. However, the trade-off between reducing environmental costs and potential increased energy consumption should be considered. Financial costs and daylighting impact were not analyzed but are likely to favor lower end-use energy consumption over time.

On-site electricity generation has a similar environmental cost reduction effect as the 1.5 °C Target electricity scenario. However, the environmental cost of the photovoltaic installation should be considered, as it contributes to the embodied environmental cost of the building. Similar trends are expected as observed with the 1.5 °C Target electricity scenario.

Efficiencies of HVAC systems, particularly cooling systems, are expected to improve. As a sensitivity analysis, the chiller and heat pump efficiencies were increased to a SEER of 8.5, resulting in decreased environmental costs and smaller differences between building options. The common characteristics of 20% WWR and north–south orientation remained consistent, favoring well-insulated buildings. For heavyweight buildings with passive insulation, glazing performance often improved while airtightness decreased. This aligns with previous research indicating higher overheating risks in airtight buildings with low $U$-values [7, 22]. Other buildings showed improved airtightness while maintaining the same glazing performance.

## 5. Conclusion

This paper explores building strategies for climate robust buildings through a parametric study considering both the operational and embodied environmental impact.

Considering the building characteristics, except the building orientation, all characteristics influence both the operational and total E-LCC of the building scenarios. Characteristics linked to the windows, with WWR as most important one, had a crucial influence on minimizing the operational and full E-LCC.

A Pareto front optimization is applied minimizing both the life cycle environmental cost and the operational environmental cost. HVAC systems and electricity mixes are found to influence the optimal buildings, but a WWR of 20% and north–south oriented windows are common across most optimal buildings. Insulation levels play a crucial role in minimizing heating demand and controlling the increase in cooling demand. Solar shading is required when heating is provided by electricity as the cooling demand has a higher importance in this case, and changes in the electricity mix can affect the optimal solutions.

This research showed that only focusing on the operational impact in the optimization process might lead to buildings with higher embodied impact. The research therefore underscores the importance of adopting a holistic life cycle approach and considering both operational and embodied environmental impacts in building design. It emphasizes the need to optimize building characteristics while addressing climate change challenges. By incorporating a comprehensive assessment of environmental impacts, designers can make informed decisions to minimize the overall environmental cost of buildings.

Future research should explore additional factors such as night cooling, HVAC system performance under climate change, financial costs, and visual comfort. Incorporating these factors will provide a more comprehensive understanding of the optimal building design strategies. Additionally, the integration of on-site electricity generation and the evaluation of the environmental cost of photovoltaic installations should be considered in future studies. Overall, further investigation is needed to refine and expand the knowledge on achieving sustainable and environmentally friendly buildings in the face of climate change.

## Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

## Funding

This work is supported by Research Foundation Flanders (FWO) [1S97418N] and is part of the PhD research 'Towards future-proof buildings in Flanders: Climate and Life Cycle modeling for resilient office buildings'.

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