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Assessing the Influence of Architectural Parameters on the Environmental and Daylight Performance of a Mid-Rise Office Building

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Abstract

Buildings are major drivers of environmental damage, including climate change and resource depletion. Yet, they provide essential functions to human society, including shelter, thermal comfort and others. To date, most existing research has typically focused on trying to optimise one of the many services that buildings provide, or to improve their environmental performance while omitting the additional comfort they provide, or their geometrical features. This master thesis addresses this gap in existing research on the environmental performance of buildings by considering the often neglected factors of daylight performance and geometric parameters. The study focuses on evaluating the effect of various parameters on the thermal energy demand, embodied environmental flows, and spatial daylight autonomy (SDA) of a parametrically modelled mid-rise office building floor. Buildings are modelled as sets of rectangular sections in plan views (referred to as 'wings') with different functions, e.g. offices and circulation. Findings highlight the significant influence of the window-to-wall ratio (WWR) and building shape parameters, particularly the number and width of the wings of building, on all the studied metrics. Specifically, the WWR seems to primarily affect the SDA and to a lesser extent the thermal energy demand. Additionally, the width of the wings appears to significantly influence embodied environmental flows and the SDA, leading to a trade-off between these two metrics. Finally, the self shadowing effect induced by the shape of the building affects the thermal and lighting performance, but further research is needed to explore this aspect in more detail. The developed research methodology proves to be effective in easily assessing the relationships between geometric parameters and energy and lighting performance, but still offers room for improvement. This study calls for future research to delve deeper into the influence of geometric parameters on buildings, expanding the knowledge in this field.

Acknowledgements

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Table of Content

Abbreviations

GHG	GreenHouse Gas
HVAC	Heating, Ventilating and Air Conditioning
IM	Insulation Material
LCA	Life Cycle Assessment
RL	Room Length
RW	Room Width
SD	Spatial Distribution
SDA	Spatial Daylight Autonomy
WL	Wing Length
WN	Number of Wings
WP	Wing Position
WWR	Window-to-Wall Ratio

1. Introduction

As the global community faces the pressing challenge of global warming, the need to mitigate its effects has become increasingly urgent (IPCC 2023 [71]). While various sectors contribute to the overall human impact on the planet, the construction industry stands out as a significant contributor. (Globalabc 2022 [75]) Within this sector, offices represent one of the most common building typologies, further amplifying their environmental footprint. Understanding and addressing the environmental implications of office buildings is therefore crucial for achieving sustainable development goals.

One of the most prevalent methodologies for evaluating the environmental performance of buildings is Life Cycle Assessment (LCA) (Chandrasekaran et al. 2022 [14]). LCA provides a comprehensive framework for assessing the environmental impacts of a building throughout its entire life cycle. This methodology has been normalised by various organisms around the world. For instance, the ISO 14044 decomposes the life stages of an assessed building into four main stages [72] : the production stage, the construction stage, the operation stage, and finally the end of life stage. The production stage includes the extraction and the transformation of the construction materials. The operation stage includes all the energy expenses related to the building and made by its inhabitants while they are occupying it. The end of life stage includes the energy needed for the demolition of the building, as well as disposal and potential recycling of its materials. For every stage, every energy expense associated with the transportation of materials is also taken into account.

The energy used during the life cycle of the building is commonly divided in two main categories : embodied energy and operational energy. Embodied energy refers to the energy consumed in the extraction, manufacturing, transportation, and construction processes associated with building materials and components. On the other hand, operational energy includes the energy consumed during the building's day-to-day operation, including heating, cooling, lighting, and appliances.

In recent years, advancements in technology have significantly reduced the operational energy demand of office buildings. Consequently, the importance of embodied energy in the overall environmental performance of buildings has started to gain prominence (Röck et al. 2020) [51]. Early design decisions, which primarily impact embodied energy, now have a significant role in determining the sustainability of office buildings. (Zaker 2022 [67])

Structure of the Thesis

Section 2 provides some insights on the current state of the knowledge on the topic. An overview of the various researches that apply LCA to office buildings is presented and includes an in-depth analysis of a paper that has very similar objectives to ours. The exact research question of this thesis is then formulated at the very end of this section.

Section 3 describes the overall research methodology scheme developed and employed for this thesis with its several steps.

Section 4 details those steps by providing explanations on their execution and the tools used to reach the different milestones.

Section 5 presents the different results obtained and their interpretation. Individual conclusions are also formulated throughout this section. They are articulated together to formulate some recommendations for the practitioners at the end of the section.

Section 6 compares the results obtained and our conclusions to the ones of other similar studies and lists the various limitations of this study as well as its contributions to the literature.

Section 7 concludes this thesis by synthetizing the main attention points of the whole study.

2. Literature Review

Offices are one of the most common architectural programs existing. However, far more studies have been conducted on residential buildings. Thus, the state of knowledge on offices still has some major gaps to fill. The following table gives an overview of papers that apply LCA to office buildings, as well as the kind of model they apply it on, and the stages they include. The transportation column reports whether the paper takes the transportations between the different stages into account or not. The production stage includes the extraction of the materials as well as their processing as those stages are almost always studied together.

Table 1: Summary of main studies focusing on the life cycle assessment of office buildings

Ref	Assessed Models			LCA Stages				
	Case Studies	Case Studies + Variations	Entirely Parametric Models	Production	Construction	Operation	End of Life	Transportation
Wu et. al. 2011 [66]	×			×	×	×	×	
Asdrubali et al. 2013 [8]	×			×	×	×	×	×
Bismas 2014	×			×	×	×		
Zhang et al. 2015	×			×	×	×	×	×
Peng 2016 [46]	×			×	×	×	×	×
Najjar 2017 [45]	×			×		×	×	×
Thiel et al. 2013 [62]	×			×				
Victoria et al. 2017 [64]	×			×				
Victoria et al. 2018 [63]	×			×				
Wang et al. 2018 [65]	×			×	×	×		×
Gangolells et al. 2020 [21]	×			×	×	×	×	×
Marique et al. 2018 [41]	×			×		×	×	×
Chau et al. 2012 [17]	×			×	×			×
Tevis et al. 2019 [61]	×			×	×	×	×	×
Ajayi et al. 2019 [3]		×		×	×		×	

Zaker Estheghamati et al. 2022 [67]		×		×	×	×	×	
Airaksinena et al. 2012 [2]		×		-	-	-	-	-
Azzouz et al. 2017 [10]		×		×	×	×		
Moschetti et al. 2019 [44]		×		×		×		
Luo 2022 [37]		×		×	×	×	×	×
Gustafsson et al. 2017 [26]		×		iNSPiRe Stages				
Alves et al. 2018		×				×		
Garcez et al. 2018 [22]		×		×	×		×	
Robertson et al. 2012 [50]		×		×	×			×
Ehsan et al. 2019 [6]		×		×		×		
Larivière-Lajoie et al. 2022 [35]		×		×	×	×	×	×
Shahbazi et al. 2019 [55]		×				×		
Alshamrani 2015 [4]		×		×	×	×		
Potočnik et al. 2021		×						
Gauch et al. 2023 [23]			×	×	×	×		×
Hasik et al. 2019 [27]			×	×		×		
Marino et al. 2017 [40]			×			×		
Taborianski et al. 2012 [60]			×	×	×	×		×
Azari 2014 [9]			×	×	×	×	×	×
Méndez Echenagucia et al. 2015 [42]			×			×		

Based on Table 1, it can be observed that case studies are the most widely used research methodology to investigate office buildings. This methodology involves conducting a detailed LCA of the examined building, which often yields results on the relative importance of each life cycle stage and building component, such as structure, foundations, floors, roof, and envelope. A recurring finding among several exhaustive case studies conducted in various climates, including Wu et al. 2011 [66], Asdrubali et al. 2013 [8], Bismas 2014, Zhang et al. 2015 [68], Peng 2016 [46], Azzouz et al. 2017 [10], and Najjar 2017 [45], is the significant importance of the operational stage. This result is further supported by the review paper of Abd Rashid et al. 2015[1].

However, Ramesh et al. 2010, Ibn-Mohammed et al. 2013 [30], and Cabeza et al. 2013 [12] suggest that while the operational stage is the main contributor, self-sufficient buildings can be counterproductive due to a notable increase in embodied energy. This viewpoint is corroborated by Georges et al. 2015 [24] and Mirabella et al. 2018 [43], who assess the emissions of Net Zero Energy Building (NZEB) concepts and find a significant rise in embodied emissions as operational emissions decrease. Additionally, Röck et al. 2020 [51] review a substantial number of case studies and confirm the observed shifting trend between embodied energy and operational energy.

On the other hand, case studies have their limitations. Pomponi et al. 2018 [47], in their review of the current state of LCA literature, find that comparing case studies is challenging due to significant differences in their results. This finding is supported by Cabeza et al. 2014 [13], who note that although numerous building case studies exist, they often focus on exemplary buildings rather than common ones. As case studies rely on a limited number of already constructed cases, there is a limit to the generalisability of their conclusions. Jusselme et al. 2018 [31] assess the limitations of applying LCA in practice and suggest that current tools are too resource-intensive to be applied in the early stages. They advise the creation of a more parameters-based assessment methodology. This suggestion is further supported by Roberts et al. 2020 [49], who find that LCA is frequently employed too late in the design process and advocate for the use of parametric tools to streamline the application of LCA in architectural practice, which is confirmed by Lützkendorf 2018 [38]. Hollberg et al. 2016 [29] developed a parametric tool to assist designers in their process by computing in real time the LCA of the geometry on which they are working. They proved its efficiency by applying it to a residential building.

Table 2 lists papers that apply LCA to office buildings and varies some parameters of their case studies, or study completely theoretical buildings. The categories of the parameters varied are provided as well.

Table 2: Summary of studies focusing on the life cycle assessment of office buildings, using a parametric approach

Ref	Service Life	Focus	Daylight Measured	Parameters Considered							
				Shape	Internal Layout	Structure	Envelope	Construction System	Energy Production	HVAC System	Usage
Ajayi et al. 2019 [3]	30 years	Energy						×			
Zaker Estheghamati et al. 2022 [67]	50 years	Energy						×			
Azzouz et al. 2017 [10]	60 years	Energy				×			×	×	×
Airaksinena et al. 2012 [2]	/	Energy									
Moschetti et al. 2019 [44]	60 years	Energy						×	×		
Luo 2022 [37]	50 years	Renovation					×		×		
Gustafsson et al. 2017 [26]	30 years	Renovation					×		×	×	
Alves et al. 2018 [5]	20 year	Renovation	×				×		×	×	×
Garcez et al. 2018 [22]	50 years	Structure				×					
Robertson et al. 2012 [50]	50 years	Structure and Envelope				×	×				
Alshamrani 2015 [4]	60 years	Structure and Envelope				×	×	×			
Potočnik et al. 2021	/	Lighting	×								
Ehsan et al. 2019 [6]	10 years	Envelope					×				
Larivière-Lajoie et al. 2022 [35]	50 years	Envelope					×				
Shahbazi et al. 2019 [55]	/	Lighting	×				×				
Gauch et al. 2023 [23]	/	Energy		×		×	×				×
Hasik et al. 2019 [27]	60 years	Energy		×		×	×		×		
Marino et al. 2017 [40]	/	Energy					×				

Taborianski et al. 2012 [60]	60 years	Envelope					×				
Azari 2014 [9]	60 years	Envelope					×				
Méndez Echenagucia et al. 2015 [42]	/	Energy					×				

This table reveals that the envelope is the most extensively researched building component, which is reasonable considering its impact on most of the energy expenditure sources in a building. Additionally, we find that the majority of those studies focus on evaluating the performance of building components (such as structure, envelope, and construction system) and building systems (including energy production, HVAC, and usage). However, two significant gaps can be identified :

- First, only three papers consider the lighting comfort and daylight performance of the building. It is crucial to acknowledge that modifications made to the envelope for enhancing the environmental performance of a building directly affect its daylight performance and the comfort of its occupants. Therefore, daylight metrics should always be considered as a balancing factor when researching ways to improve the environmental performance of an envelope, as concluded by Shahbazi et al. 2019 [55].

- Second, only two papers take a step back to assess the influence of the building's shape on the entire system, and none of them considers the internal layout of the building. The internal layout and the shape of a building are the two primary parameters fixed by an architect during the design process. As they form the fundamental structure of an architectural project, they play a significant role in defining every other building component.

The conclusions drawn in this paragraph are supported by several review papers. For instance, Hemsath et al. 2015 [28] conducted a review that affirms the lack of links between geometry and performance in the existing literature. Similarly, Kistelegdi et al. 2022 [33] conducted a review and acknowledged that the literature in this field is still in its early stages; however, they noted that the results from studies involving geometry show great promise. Moreover, Latha et al. 2022 [36] conducted a review and confirmed that papers focusing on geometry consistently find a significant influence on energy consumption. Furthermore, Du et al. 2020 [20] conducted a review that primarily examined the internal layout and concluded that it exerts a greater impact on energy performance compared to occupant comfort. It is important to note that these papers extend beyond the realm of offices, broadening the scope of their analysis.

Among the limited number of studies investigating the influence of shape on building performance, Gauch et al. 2023's paper [23] stands out due to the extensive range of parameters examined. Their study aims to address the observation that geometric parameters are under-explored in LCA studies focusing on buildings. They assume that conclusions drawn from global assessments of buildings can inform practical decision-making and have a tangible impact. The research methodology begins with the creation of a parametric model representing a generic building, with scenarios defined by varying the parameters of the base model. Energy simulations are then conducted on the generated models to evaluate the thermal needs of the scenarios. Finally, the results' variations are analysed through a global sensitivity analysis.

The study reveals that the surface area of each floor is the most influential parameter on thermal needs for residential occupancy, followed by the WWR. These two parameters are interconnected through the building's compactness : a smaller building area relative to the envelope area results in lower thermal needs. The study also highlights that fenestration design holds a greater importance than optimising envelope insulation. For WWR, a reduced ratio leads to lower energy demands. However, these influences are proportionally reduced when simulating an office occupancy due to higher occupation density. The study further observes a trade-off between heating and cooling demands, as well as between the influence of shape parameters and the WWR.

One of the key observations from this study confirms that the design choices made by architects significantly impact the overall performance of the resulting building, even when individual components are optimised separately. These results encourage further investigations to assess the influence of parameters across a wider range of variations, particularly for building shape. The study only considered variations in the dimensions of a simple rectangular building footprint, while real architectural practice encompasses a much broader variety of typologies that merit exploration.

Research Question

Compared to the case studies, there is a relative minority of studies relying entirely on a parametric approach to identify the building components and parameters that are influential on the embodied and operational flows of office buildings. Among those studies, almost none of them considers architectural parameters such as the shape of a building in its scope. Moreover, all of those studies only evaluate energy-related metrics, and don’t take into account the daylight performance of the studied spaces, although it is a crucial aspect of working spaces such as offices.

This research intends to start bridging this gap by evaluating the performance of office buildings in terms of energy and lighting metrics, while varying a range of parameters that include shape-related parameters.

3. Research Design

3.1. Research Methodology

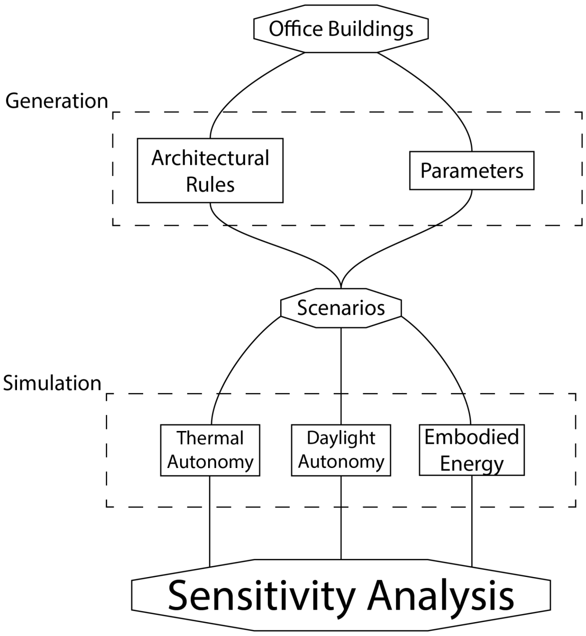


Figure 1: Overall research approach

The methodology employed for this study consists of three phases: scenario generation, simulation conduction, and statistical analysis of the simulation results.

In the first phase, scenarios are created as models of generic office building floors. These models are parametrically generated based on a set of geometric parameters and architectural rules. The rules are derived from existing literature and the authors' experience, while the parameters are selected based on their popularity in the literature and their relevance to this study. In this study, the building's shape in particular was discretized into a wide range of parameters.

The simulations were conducted to assess two major aspects : the environmental performance of the scenarios and their daylight performance. The environmental performance assessment focuses on two main metrics : the embodied flows, which include embodied water and energy, and the annual thermal energy demand, which represents the energy required for heating and cooling a building to maintain a comfortable temperature range. The daylight performance assessment only encompasses one metric: the Spatial Daylight Autonomy (SDA), but varies its spatial threshold. This metric should be accompanied by a Glare Probability analysis (Kazanasmaz et al. 2016 [32]) to ensure that the spaces don't receive too much light. However, such a simulation requires too many details, therefore it is out of the scope of this study.

The simulation results were analysed using a Python script. The script parses through the results and organises each data point into the appropriate location within a customised database. This database facilitates the comparison of the results and enables the generation of relevant graphs and diagrams.

3.2. Scope

This study examines a set of parametrically generated office floor models situated at mid-height within a theoretical mid-rise office building. These models are designed to represent a range of simple European office buildings without immediate context, such as office buildings located in business parks.

The parameters used in the generation process have a predetermined set of values. Each unique combination of parameter values generates a model, referred to as a scenario for subsequent analyses. The parameters used to generate the models include:

- The width and the length of the wings of the building,
- The shape of the building, which comprises and arrangement of wings articulated by squares,
- The degree of partitioning of the internal spaces,
- The window-to-wall ratio of the façades,
- The internal distribution of the spaces,
- The insulation material for the thermal envelope of the building.

The different sets of values provided to these parameters will be detailed in the Section 4.1.2. Along with the expected effects of these parameters.

While the models are not based on specific case studies, the weather data used for the analyses correspond to the city of Brussels, Belgium. This city is located in a moderately temperate climate zone of Europe, without any distinct climatic requirements. The weather data used in this study are sourced from the EnergyPlus website. Figure 2 illustrates the solar radiation levels and the average temperatures for the city.

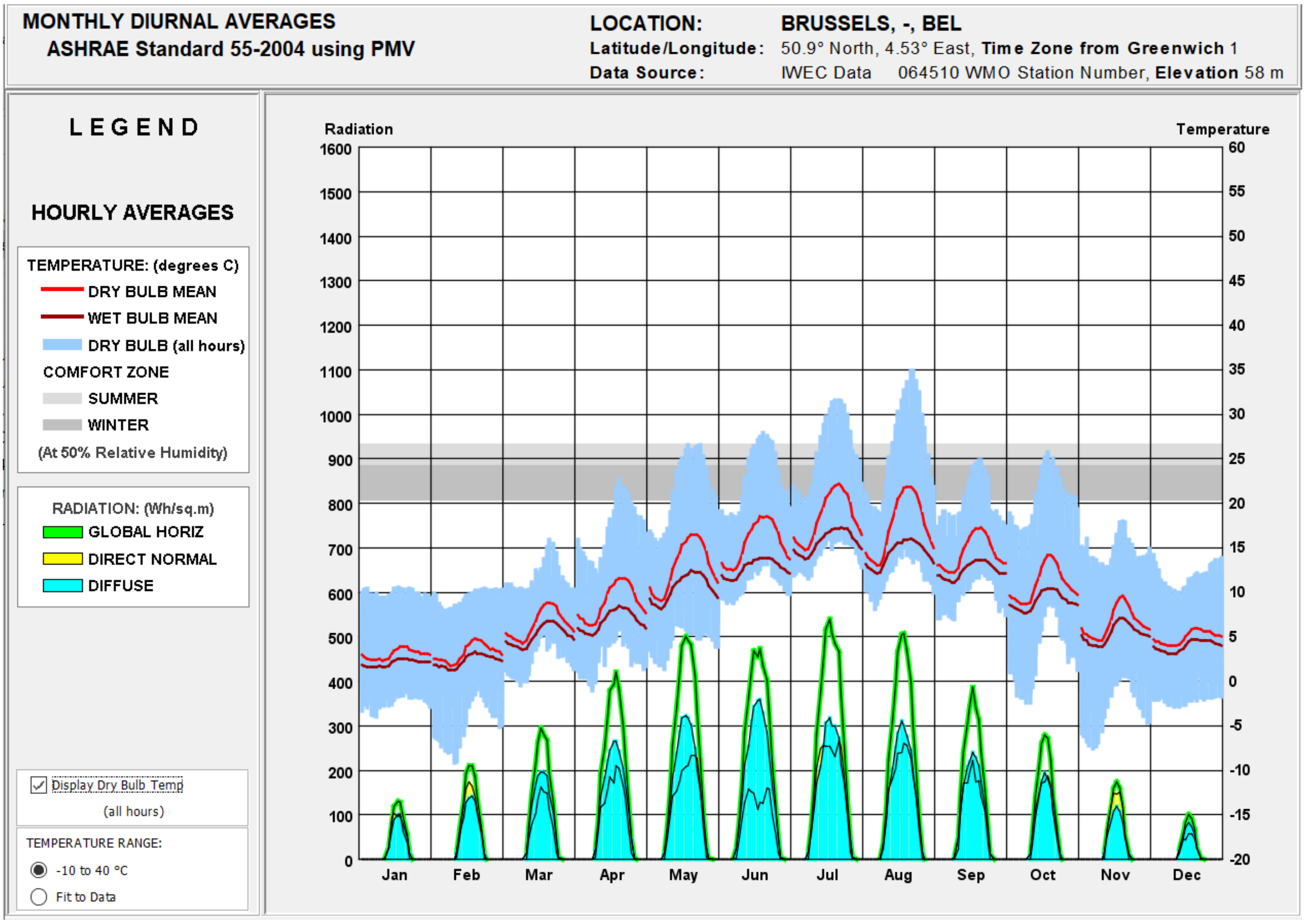


Figure 2: Monthly diurnal averages for Brussels, Belgium

We can observe that these temperatures are mostly located below the comfort zone defined by the Climate Consultant software, which ranges from 20°C to 24°C. These data will be used in the daylight and thermal simulations.

For the embodied flow calculation, the life cycle duration of the models is fixed at 60 years and the precise life cycle duration of each material and assembly is taken into account. The life cycle assessment (LCA) stages follow the ISO 14044 [72] norm, and the stages included in this study are listed in Figure 3.

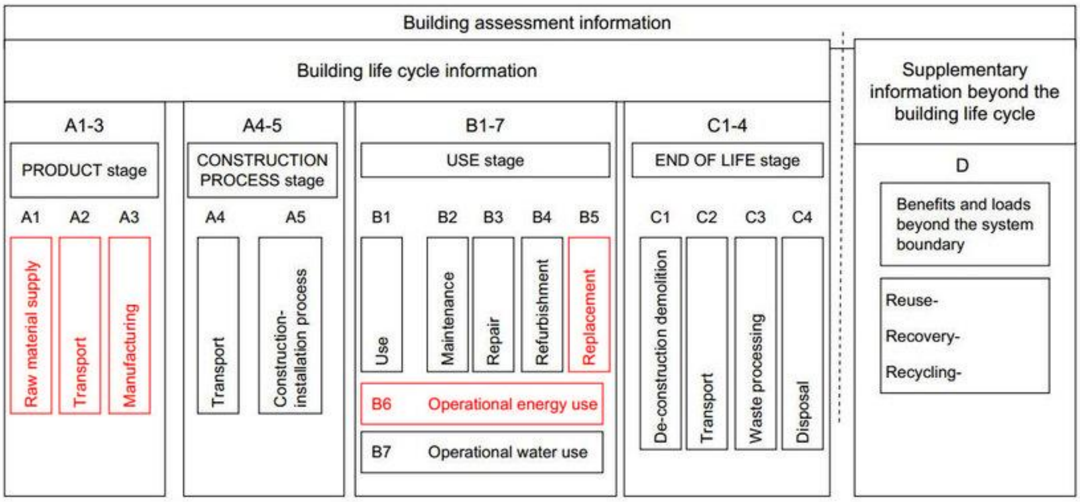


Figure 3: Life cycle stages considered in this work. Note: adapted from EN15978

4. Method

4.1. Generating the models

4.1.1. Architectural Rules

The initial step of this methodology involves generating scenarios for the analyses by parametrically modelling a set of generic office building floors. To ensure architectural coherence, certain rules were established to limit the range of possibilities to a manageable extent. Those rules were defined based on common architectural good practices as well as guidelines prescribed by the 5th edition of the Architects' Data [73].

Serving and Served Spaces:

The models consist of working spaces, including office rooms, resting spaces, and meeting rooms, as well as service spaces comprising sanitary facilities, vertical circulations, and storage rooms. Each working space must have one to two corresponding service spaces.

Form :

The working spaces are designed as rectangles, while the service spaces take the shape of squares with the width of a working rectangle as their side length.

Function ratio :

Half of the working rectangle area is composed of defined rooms. They include offices and one meeting room per rectangle. The remaining half serves as a multi-purpose space, whose use is to be defined by the users as prescribed in the Architects' Data [73].

Lighting :

Office rooms and meeting rooms are required to have direct access to natural light from the exterior. Light well configurations are not considered in this study for simplicity. The multi-purpose area may not always have direct access to sunlight.

Continuity :

The defined rooms must be contiguous for at least half the length of a working rectangle.

Horizontality :

For ease of implementation, there are no variations in ceiling or floor height across a single floor.

4.1.2. Parameters

The dimensions of the office rooms (see Figures 4 and 5) are determined based on the Architects' Data [73] guidelines, which outline five mandatory dimensions to be followed:

- A 60 cm setback between the desk and a window.
- An 80 × 160 cm desk area.
- A 1.5 m² movement area in front of the desk.
- A 60-80 cm access space next to the desk, depending on what is beyond it.

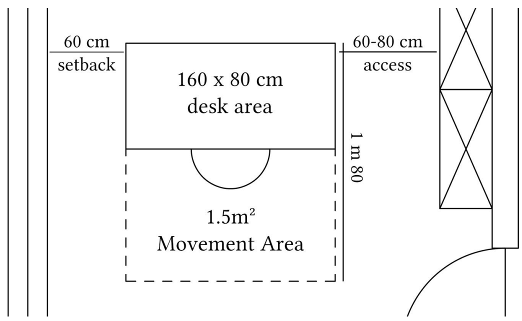


Figure 4: Typical office floor plan.

- A room size of 3.40 × 1.90 m for a single workstation room, or 3.40 × 3.60 m for a 2-workstation room (width × length).

Using these dimensions, we can fix the set of lengths and widths for the definition of the office rooms :

- For the width, 1.60m is added twice to the minimum 3.40m,
- For the length, another 1.80m is added to the 3.60m needed for a 2-workstation room.

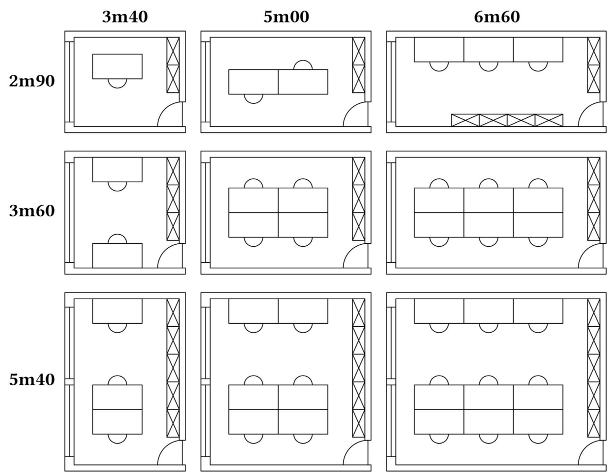


Figure 5: Typical dimensions of offices

The width of the room is expected to play a significant role as it directly determines the width of the wing, thereby influencing various aspects examined in this thesis. It affects the floor area, the depth of the rooms, and ultimately, the overall compactness of each building wing. The compactness of a wing has been recognized as a key factor in determining the thermal energy demand, as highlighted by the study of Gauch et al. 2023 [23]. Their findings reveal notable trends that underscore its importance.

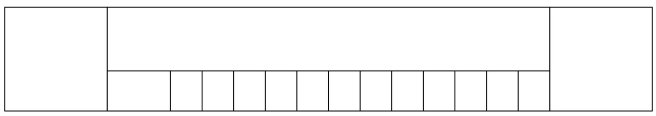
On the other hand, the length of the room primarily impacts the building's occupancy density by allowing for an increased number of workstations within each room. Consequently, it is expected to exert a significant influence on the embodied energy of the building. In addition, its impact on the thermal and daylighting aspects should be relatively minor.

The Architects' Data [73] also describes two possible types of spatial distribution for the office rooms defined : one divides the width of the wings into two halves, and the other divides it into three parts. For this study, only the first type of spatial distribution was modelled. Combining the 2-segment spatial distribution with the 0.5 "Function Ratio" and "Lighting" rules results in three possible configurations :

The "full length" configuration :

This configuration fills the entire length of a wing with office rooms. The office rooms in a single wing are all uniformly oriented, and the free-use space and corridor merge to create a large but very long open space. An example scheme is illustrated in Figure 6.

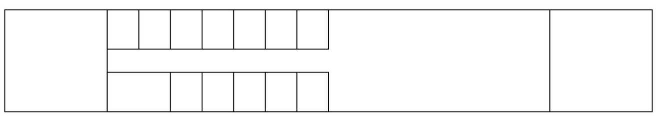
Figure 6 - "Full length" spatial distribution



The "full width" configuration:

In this configuration, the office rooms take up the entire width of the wing and half its length. This allows the offices to face two opposite orientations, and the free-use space becomes more compact. This configuration creates a clear separation between the working area and the mixed-use area and can be easily acoustically isolated by closing the entrance to the open space. An example scheme is illustrated in Figure 7.

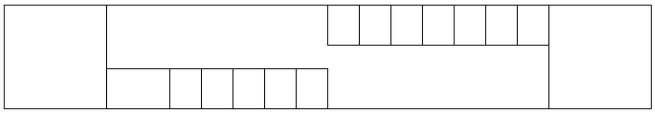
Figure 7 - "Full width" spatial distribution"



The "alternate spaces" configuration:

In this configuration, one block of office rooms from the previous configuration is moved to the other half of the wing's long side. This creates two independent halves in the wing, where the office rooms face their own mixed-use area that is not shared with the other offices of the wing. It also allows for complete isolation of one half from the other by closing their junction. An example scheme is illustrated in Figure 8.

Figure 8 - "Alternate spaces" spatial distribution



The spatial distributions within a wing are anticipated to impact the SDA by altering the number of corners and isolated spaces. However, their influence on embodied energy is expected to be minimal since the quantities of materials involved do not vary significantly due to the proximity of the considered distributions. It is important to note that the study does not encompass the influence of these distributions on thermal metrics. The reasons behind this decision will be detailed in Section 4.2.1.

Based on the rules described earlier, four simple building footprints are defined, each having one more rectangular wing than the previous one. These footprints recreate a simple closed square surrounding a patio. As per the "Form" rule, these footprints consist of working rectangles joined by service squares. The length of the wings takes three definite values (29m, 38m, and 49m) based on the set of possible room lengths. Although the room lengths do vary slightly from the original desired dimensions, the differences are kept as small as possible without significantly reducing the range of wing length variations. The exact lengths for the rooms are provided in Table 3::

Table 3: Overall geometric specifications of room sizes and wings

Wing Lengths	Number of Rooms for 2.9 - 3.6 - 5.4m	Corrected Room Lengths [m]
29m	10 - 8.06 - 5.37	2.9 - 3.63 - 5.8
38m	13.1 - 10.55 - 7.04	2.92 - 3.45 - 5.43
49m	16.8 - 13.61 - 9.07	2.88 - 3.5 - 5.44

These building shapes are expected to influence lighting and thermal metrics in a similar manner as the room widths do : by determining the compactness of the wings. As the length increases, the building becomes less compact, reducing the shadows it casts on itself and potentially increasing the thermal energy demand according to Gauch et al. 2023 [23]. The full set of shapes is presented in Figure 9.

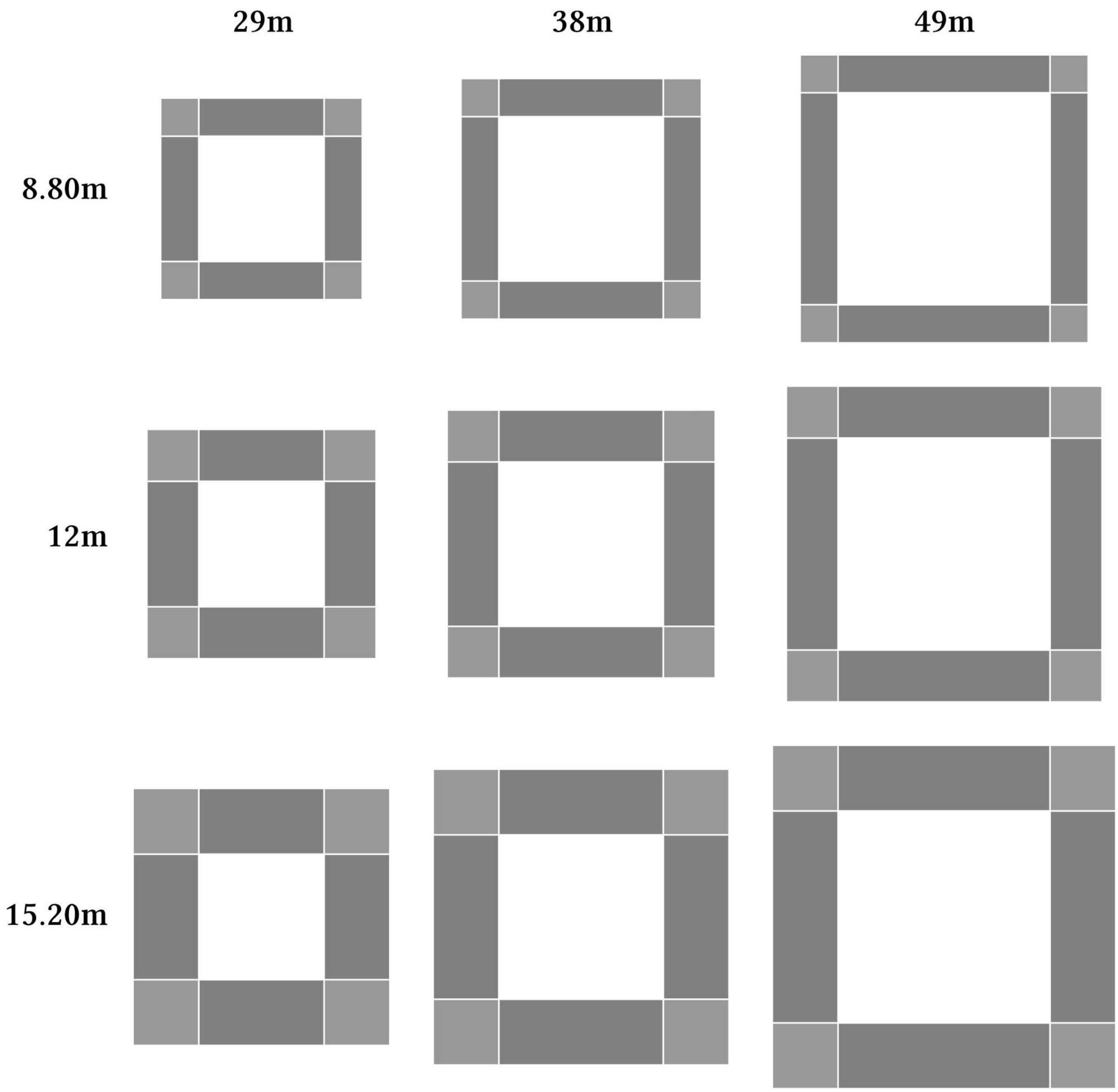


Figure 9: Plan view of the different building shapes considered and their dimensions

The WWR is another geometric parameter considered. It is defined as the ratio of the total glazed area to the total façade area. Based on the findings of Francesco Goia (2016) [25] and Ma et al. 2015 [39] regarding optimal WWR ranges for minimal energy needs, three values were chosen : 22%, 30%, and 38%. The windows are evenly distributed in each wing, positioned in the centre of the room length, 1.20 m above the ground, and extending up to 40 cm below the ceiling. Only their width varies based on the WWR and the room length. This parameter is expected to influence all the metrics considered, as it determines the amount of light entering the rooms and slightly affects the total quantity of thermal insulation.

The insulation set comprises three different materials selected for their different environmental performance. The thickness assigned to each material was defined to achieve a U-value of 0.275, equivalent to 120 mm of rockwool insulation. This reference value comes from the Energy Plus insulation library, derived from the ASHRAE norm for our climate zone. It is also slightly better than the 0.35 prescribed in the study of Krolija et al. 2013 for office buildings built around 2010. The Ubakus online calculator [69] was used to determine the appropriate thickness for the other insulation materials. The specific heat and density of the materials were obtained from the EPiC database [70], while the default thermal conductivity values for each material in the calculator were used. The resulting set of insulation materials and thicknesses can be found in Table 4 :

Table 4: Characteristics of insulation materials used

Insulation material	Specific Heat [J/(kg·K)]	Density [kg/m³]	Thermal Conductivity [W/(m·K_]	Thickness [mm]
Polyurethane	1800	30	0.05	150
Rockwool	840	70	0.04	120
Cellulose	1400	50	0.04	120

4.1.3. Algorithm

This section provides a description of the algorithm developed in the Grasshopper environment to implement the different parameters used in this study and generate the corresponding scenarios.

The algorithm follows these steps:

1. The width of the building wings is set by drawing a square with the desired width as its side length.
2. These squares are then copied to every possible position for each potential wing length.
3. The wing areas are defined by connecting the corners of consecutive squares with parallel lines.
4. Each shape is defined by selecting the appropriate set of parallel lines and corner squares.
5. Every wing is divided into two halves by connecting the midpoint of their extremities with a straight line.
6. This line is offset on both sides by half of the circulation size, which is fixed at 2 metres. This defines the central circulation corridor within the wing.

7. The office rooms are defined by dividing the side-long rectangles based on the number of rooms that can fit within the length of each wing, considering the desired room length.

8. To prepare for the extrusion and adaptation steps of the algorithm, each wall is divided to differentiate the sections with full height and those hosting openings such as doors or windows.

9. The meeting room of each wing is defined by removing a partition wall between the first two rooms of each wing.

10. The final step of the generation process is to select the appropriate sets of rooms to compose the different spatial distributions.

11. Finally, the various types of lines are transformed into rectangles before being extruded and adapted to meet the requirements of the analysis tools used.

By following these steps, the algorithm generates the desired building configurations and incorporates the specified parameters for further analysis.

4.2. Analysing the Scenarios

4.2.1. Heating and Cooling Energy Demands

Each scenario underwent a thermal simulation to assess the influence of every relevant parameter on the thermal energy demands of the system. However, a cut in the scenario set had to be performed in order to reduce the total computation time of the simulation process. To perform this cut, the temperature is assumed to be roughly equivalent in every zone of a single wing. This assumption is supported by two facts :

- First, it was assumed that the temperature is roughly equivalent in every zone of a single wing. This assumption is based on the fact that air exchanges between different spaces within a wing are facilitated by the movements of the occupants. Therefore, complete clustering of different zones is unlikely to occur.

- Second, the partition walls do not contain insulation materials, which means that any significant temperature difference between adjacent rooms would be reduced within a reasonable time.

As a result, the geometries of partition walls are ignored in this cut, rendering the Spatial Distribution parameter irrelevant as it depends on the locations of these walls. These assumptions are supported by Gauch et al. 2023 [23] who also performed this cut in their study for similar reasons. This cut reduces the scenario set by a factor of three and removes the most computationally intensive elements, enabling smoother and faster simulations. The thermal zones assessed are defined as the closed volumes of each wing for every considered scenario.

Furthermore, since the insulation materials' thicknesses were chosen to achieve a U-value of 0.275, their thermal performance is equivalent. Therefore, only the 120 mm rockwool insulation is retained for the analysis, further reducing the length of the scenario set by a factor of three.

The thermal simulations are conducted using the Energy Plus simulation engine, accessed within the Grasshopper environment through Honeybee. This simulation engine calculates the thermal energy flows within a given geometry with defined materials for each surface. In this case, the geometry corresponds to the closed volumes of each building wing, so only the compositions of the façades, end walls, and slabs needed to be defined. The specific composition of each type of construction element is provided in Table 5.

Table 5: Compositions of construction elements

		Input Name	**Value**
Zone Boundaries	**Façades**	Boundary condition	Outdoors
		Composition	100 mm clay brick 200 mm concrete block Variable insulation 19 mm gypsum board
		Windows Composition	Default double glazing windows
	End Walls	Boundary condition	Adiabatic
		Composition	Default wall composition
	Floor and Ceiling Slabs	Boundary condition	Adiabatic
		Composition	Default slab composition

After defining the building geometry and material compositions, the next step is to establish the temporal and weather parameters for the thermal simulation, as well as the type of HVAC installation to be considered. For this study, the weather data of Brussels is used as input, representing the climate conditions of the location.

The HVAC installation is modelled as perfect, which means that the system is assumed to effectively compensate for all heat gains and losses that exceed the defined temperature range within the zones at all times. The simulation will provide the total energy required to be either removed or added to the considered zones. These results will serve as a rational basis for comparing the different scenarios.

The specific values for this set of parameters, including the weather data and HVAC assumptions, are provided in Table 6.

Table 6: Modelling parameters

	Input Name	Value
Calculation Parameters	Weather Data	Brussels' weather data
	Analysis Period	Every hour of the year
	Timestep	Once per hour
HVAC Sizing Parameters	HVAC System	Ideal Air Load System
	Acceptable Temperature Range	21 - 24°C (default)

In the thermal simulation, the Energy Plus engine calculates the energy surplus or deficit by summing the various heat gains and losses at each defined time point, as specified in the Calculation Parameters. These loads are calculated by combining a set of factors whose values are fixed by the user. These factors are divided in two categories : the internal factors and the external factors.

The external factors primarily account for the building's surrounding context and the potential shading effects it may have. They also consider a wind coefficient that influences the air circulation around the building.

The internal factors take into consideration user behaviour and allow the user to select the sources of internal heat within the building that should be included in the calculations.

Further details regarding these input factors are outlined in Table 7.

Table 7: Environmental modelling parameters

	Input Name	Value
External Factors	Context	Own mass of the building
	Shadow Calculation Method	Averaged over multiple days
	Shadow Calculation Frequency	Updated every 30 days
	Shadow detail level	3000 points (default value)
	Solar Distribution	Only direct sun on the floor, considers the context geometry.
	Wind Coef	City context : 50% of the buildings up to 2km away are taller than 21m.
Internal Factors	Occupancy Schedule	8h - 18h
	Area / user	17m² / user
	Loads	Electric lighting, Electric equipments, People's metabolism.

4.2.2. Spatial Daylight Autonomy

In order to evaluate the lighting performance of the building, a daylight simulation is performed using the Radiance simulation engine within the Grasshopper environment through Honeybee. This simulation engine requires the input of the building's geometry and a set of analysis points, and it calculates the amount of light received at each analysis point. The simulation process involves discretizing the light sources into rays, determining their trajectory, and assessing their energy when they reach an analysis point.

Certain geometric situations such as room corners don’t have a significant influence in the global results due to the ambient occlusion effect. The way these situations are handled is decomposed in parameters whose values can be determined by the user. These parameters allow the optimisation of the computation time while keeping an acceptable accuracy of the simulation. The specific inputs used for the simulation, including the ambient parameters, are detailed in Table 8. For this study, most of the ambient parameters were kept at their default values as the focus is on comparing the results between different scenarios.

Table 8: Ambient parameters

Input Name	Value
Weather Data	Brussels' weather data
Test Points	Horizontally : 1 point every 50 cm, Vertically : 1 m above the floor.
Calculation parameters	1 ambient bounce instead of 2 to increase computation speed
Context	Partition walls, Building mass

The daylight simulation generates a table that provides the energy received by each analysis point for every hour of the year. Using this table, the SDA of the zones under consideration can be calculated using a time and a lighting threshold.

The SDA is a widely used metric that assesses the daylight performance of a given zone over an extended period of time (Kazanasmaz et al. 2016 [32]). It involves determining the proportion of analysis points that receive light and exceed a specified lighting threshold for a duration exceeding a certain time threshold. In this study, we calculated the SDA using a lighting threshold of 300 lux, which is the default value referenced in Honeybee, and time thresholds corresponding to 25%, 50%, and 75% of the occupancy period, which spans from 8 am to 5 pm. This calculation is realised via a Python script written for the purpose of this study.

4.2.3. Embodied Flows

The embodied energy of a building encompasses all the energy required for the production of its constituent materials and their assembly during the construction phase of the building's life cycle. Various databases exist that provide coefficients for a wide range of materials, enabling designers to assess the embodied energy associated with the production of the materials used in their projects. Typically, these coefficients convert the functional unit of the materials (e.g., kg, m^2, m^3, unit) into the amount of energy required for their production. This energy can be further converted into greenhouse gas emissions by applying a coefficient representing the energy mix of the specific country.

The embodied energy coefficients can be modelled based on three different methods : a process based method, an Input/Output (I/O) method, and a hybrid one that combines both of the previous. A major issue currently under investigation in the research is the significant difference between the results obtained with each method for similar case studies. Säynäjoki et al. 2017 [53] found that these differences can reach a factor 2, Chastas et al. 2016 [15] and 2018 [16] confirm the vast influence of the energy mix.

The hybrid method is considered a favourable compromise between the other two methods and generally provides more reliable results. Consequently, the EPiC database (Crawford et al. 2022 [19]) was selected as the data source for assessing the embodied energy of the various scenarios considered in this study.

The computation of embodied energy was performed using the EPiC Grasshopper plugin (Stephan 2022 [59]), which serves as a link between the Grasshopper environment and the online database, facilitating the calculation of embodied energy. The plugin requires information on the constructive assemblies used in the analysed scenarios to execute the calculation. These assemblies are defined based on two inputs: the constituent materials and the set of geometries that each assembly represents. Since the generation algorithm already generated and differentiated the constructive elements by type, only the materials for each type need to be defined. The complete set of assemblies, along with their total embodied energy, water consumption, and greenhouse gas (GHG) emissions (expressed as CO_2 equivalent), are detailed in Table 9.

Table 9: Embodied energy, water and greenhouse gas emissions of different assemblies used in the model

Constructive Element	**Composition**	**Emb E [MJ/m²]**	**Emb. W [L/m²]**	**Emb. CO_2e [kg/m²]**
Partition wall	Timber frame structure, Plasterboard on both side, Water-based paint	523.71	761.71	32.92
Façade - Polyurethane	100mm clay brick, 390x190x190mm concrete block, 150mm rigid polyurethane, 13mm plasterboard, Water-based paint	2739.15	4318.44	205.876
Façade - Rockwool	100mm clay brick, 390x190x190mm concrete block, 120mm rockwool, 13mm plasterboard, Water-based paint	1900.29	1735.92	159.046
Façade - Cellulose	100mm clay brick, 390x190x190mm concrete block, 120mm cellulose, 13mm plasterboard, Water-based paint	1493.25	1336.44	131.866
Slab	Carpet, 200mm concrete, Water-based paint	1076.7	2025.1	114.93
Doors	OSB sheet	576.88	719.88	30.04
Windows	Double-glazed window	1336	1558	101

The coefficient values used for calculating embodied energy in this study are based on Australian data, which means that the energy mix differs from that of Belgium. The review paper of Chau et al. 2015 [18] found that such difference in electricity mix has a major impact on the reliability of the greenhouse gas (GHG) values. Therefore, for the scope of this study, the GHG emissions metric will be excluded. However, embodied energy values in primary energy terms tend to vary much less according to location, as demonstrated in Stephan et al. (2013) [57] and Stephan and Stephan (2014) [58].

The calculation engine also takes into account the service life of the materials used. This means that it considers the energy required for replacing materials that do not last as long as the entire building. The service life considered for the entire building is fixed at 60 years, while the service life of other materials was obtained from the thesis of Rauf 2015 [74] and is listed in Table 10. The service life of doors could not be found specifically, but since they are relatively less significant compared to elements like partition walls and structural components such as the façade, their service life was assumed to be identical to that of the windows.

Table 10: Service lives of selected construction materials

Material	Service Life [years]
Concrete slabs	Lifetime
Façade components	Lifetime
Timber partition frame	Lifetime
Plasterboard	35
Double glazed windows	25
Doors	25
Water-based paint	10
Carpet	10

4.3. Analysing the Results

In order to analyse the large amount of raw data generated from the simulations, a data processing step is performed to organise the results and draw conclusions.

The first step involves clustering the raw data and storing the results in a custom data structure. This structure divides the initial dataset into smaller subsets that contain the results for each metric. These subsets are further divided based on the parameters considered for each metric. This division is done by identifying sets of results where only one parameter varies, and storing the results of those sets in separate lists for each value of the parameter. This allows for easy evaluation of the impact of each parameter variation on each metric. A visual representation of this data structure is provided in Figure 10.

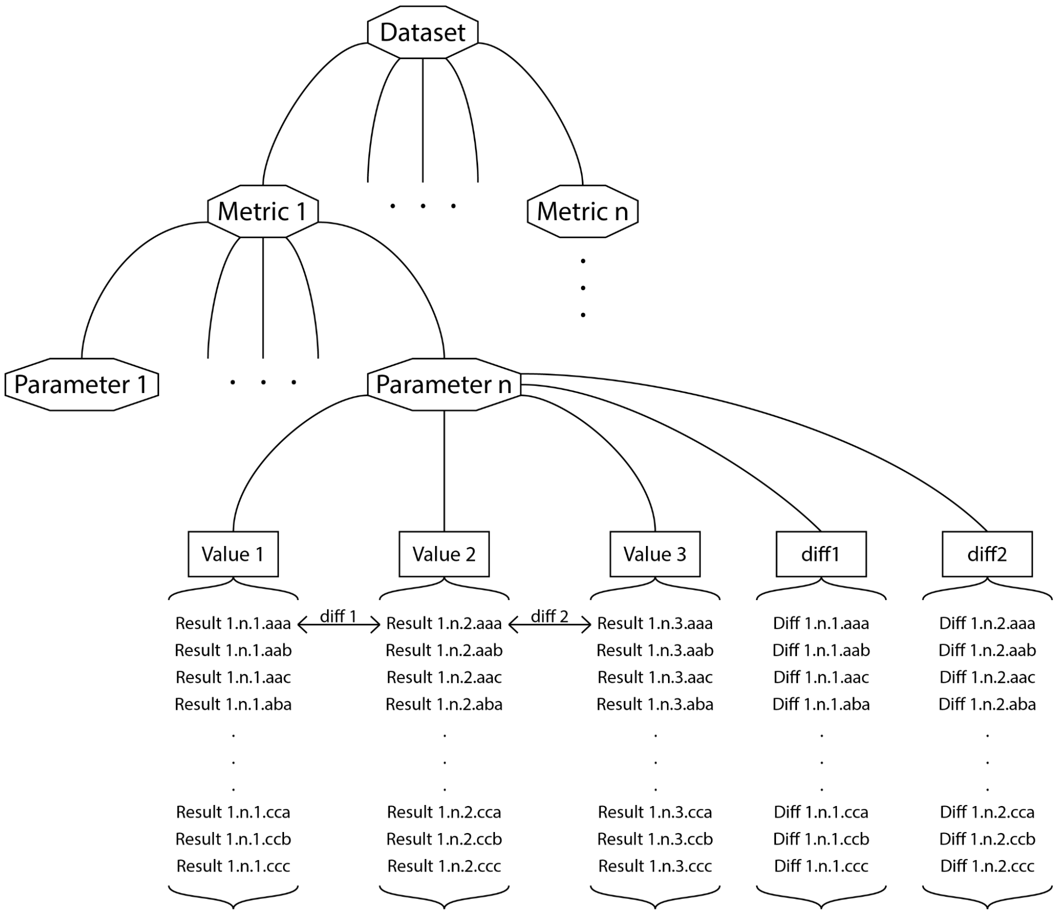


Figure 10: Data processing approach

Once the data is organised, the absolute influence of the parameters can be evaluated. The relative and absolute differences of the simulation results are computed for each variation of each parameter and stored in lists within the data structure, at the same level as the parameter values. A statistical analysis is then conducted on each list, and the results are exported in a CSV report. The statistics included in the report are as follows:

- "Count" : Number of items in the list.
- "Mean" : Average value of the list.
- "Std" : Standard deviation from the mean value.
- "Min" and "Max" : Minimum and maximum values of the list.
- "25%", "50%", and "75%" : Values below which 25%, 50%, and 75% of the list's values can be found.

The generated CSV report serves as a basis for creating graphs to visualise the results. For each field considered (Thermal, Lighting, and Embodied Flows), box plots are used to compare the influence of each parameter against each other and against the absolute average result. The box plots represent the minimum value, the mean value minus the standard deviation, the mean value

plus the standard deviation, and the maximum value of the relative or absolute difference, depending on the linearity or absence of linearity of the parameter. Based on observations from these graphs, additional graphs may be generated to further analyse specific trends that have been identified.

5. Results

This section provides a comprehensive overview of the analysis conducted, presenting the detailed results. The results are organised into the three main fields assessed in this study : Thermal, Lighting, and Embodied Flows. Subsequently, the conclusions pertaining to the various parameters involved will be elaborated upon.

5.1. Thermal Results

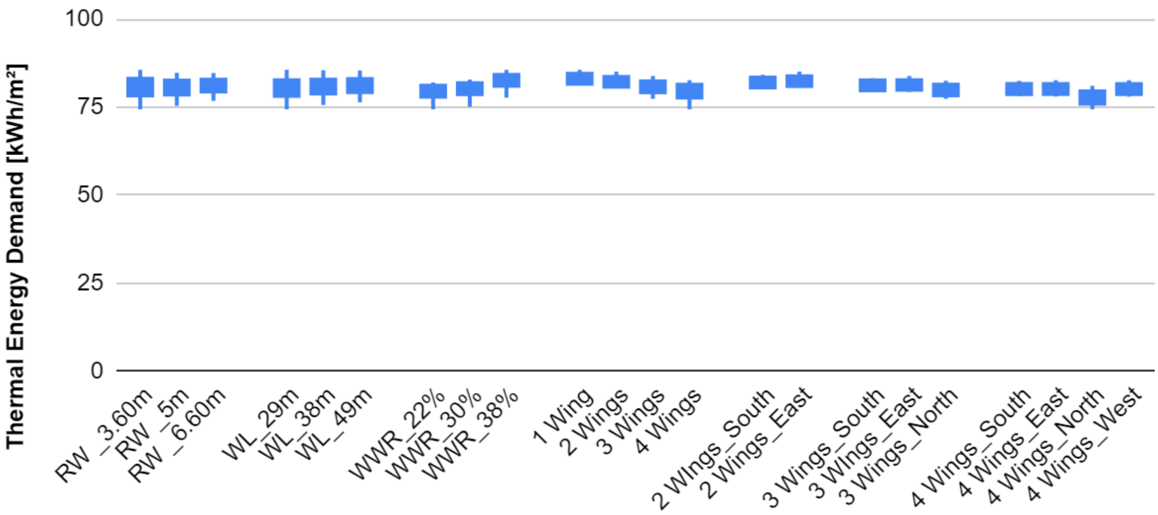


Figure 11: Annual thermal energy demand, by parameter

Figure 11 illustrates the average thermal energy demand for each parameter's values over a year. The 1, 2, 3 et 4 wings columns refer to the building shapes comprising one to four wings. The columns labelled “South”, “East”, “North” and “West” represent the average values for the related wings in the referenced shape configuration.

The amounts presented on the graph are determined by aggregating the heating and cooling demands from each analysed scenario. The results show minimal variation in comparison to the absolute values. However, the window-to-wall ratio and parameters related to the number and positions of the wings emerge as relatively significant factors. To further analyse their impact on the overall system, a graph depicting the relative variations as percentages of the total average energy demands is presented below. As described in the Section 4.3, these variations were calculated by averaging the differences between the results for each value of each parameter while keeping the other parameters fixed. This approach provides a rational estimation of the parameters' influence on the entire system.

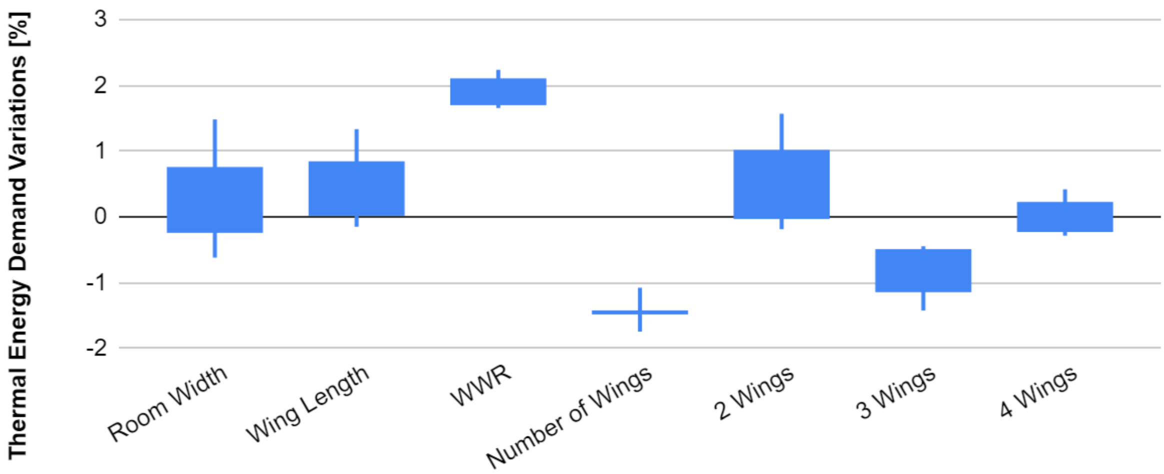


Figure 12: Annual thermal energy demand variation, by parameter

Figure 12 reaffirms the trends observed in the overall graph, highlighting the prominent effect of the WWR on energy demand. As the ratio increases, the energy demand also increases. Conversely, the number of wings appears to decrease the energy demand as the building becomes more enclosed. The absence of upper and lower boundaries for the number of wings is due to the structure of the results and the statistical analysis script, which does not allow for easy computation of descriptive statistics for this specific parameter. Hence, only an average of the averages of the four values of this parameter was calculated.

These observations align logically with wider windows leading to higher temperature gains from solar radiation, while the self-shadowing of the building reduces these radiation effects. However, the impact on the total energy demand is surprisingly small.. To gain further insights and identify more significant patterns, we disaggregate the data into heating and cooling demands, and the resulting graph is presented in Figure 13..

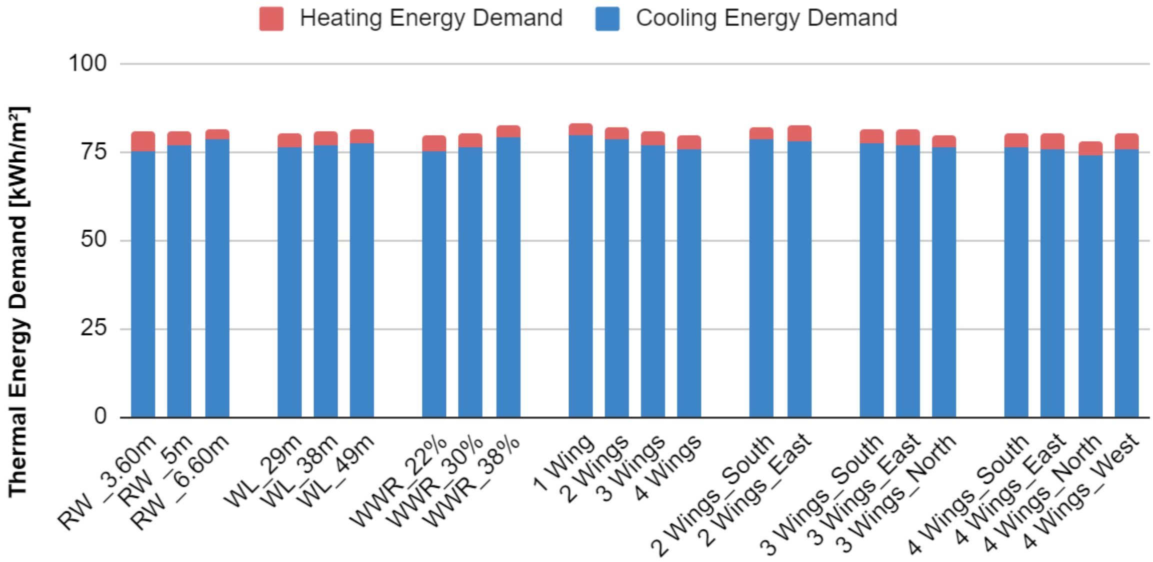


Figure 13: Annual heating and cooling energy demand, by parameter

Upon dividing the total energy needs into heating and cooling requirements, a notable finding emerges : the cooling needs surpass the heating needs by a significant margin. Building upon the earlier observations, this stark difference in the magnitude of energy demands suggests that the majority of cooling needs are not influenced by the various parameters under consideration. To further analyse the thermal needs, we further break them down into their components, and the resulting composition is depicted in Figure 14..

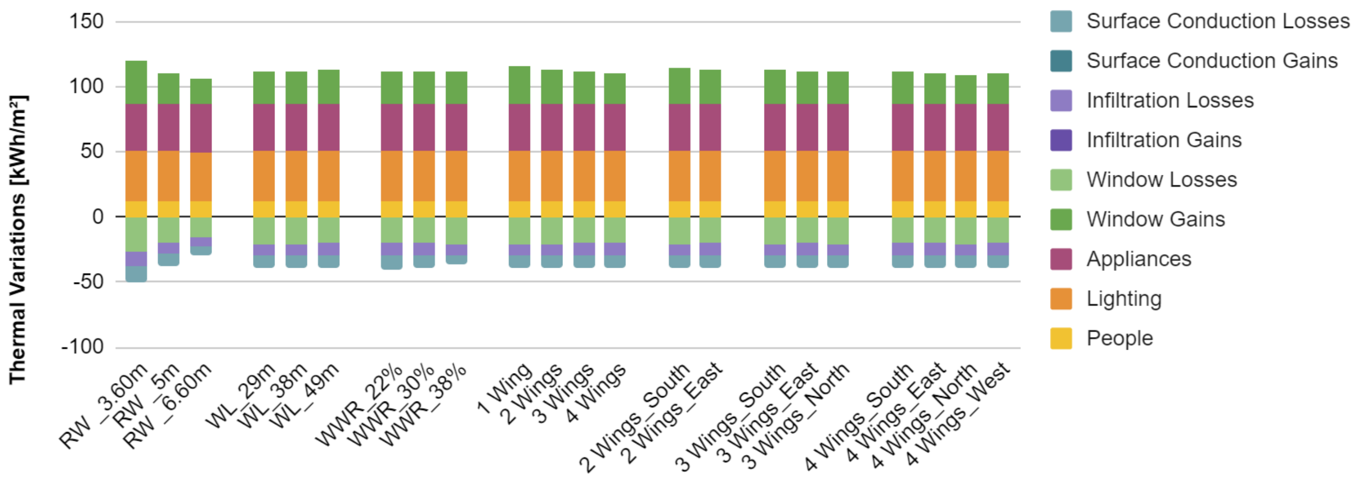


Figure 14: Annual heating and cooling energy demand, by parameter

The graph presented here illustrates the distribution of energy contributions from various sources of thermal variations, whether they involve energy addition or removal. It is evident that a substantial portion of the heating energy is attributed to electric lighting and electric appliances. These sources are predetermined in the calculation engine based on default values for office buildings. Notably, the influence of lighting presents a significant limitation to the validity of these results, as gains and losses associated with windows rank third in terms of relative importance. These window-related gains are closely linked to the amount of daylight received by different spaces, thereby affecting the need for electric lighting in the building.

Regarding the actual influence of the parameters, it becomes apparent that only the WWR, room width, number of wings, and wing positions exert an influence on the composition of the results. The WWR primarily affects heat losses through windows, which can be attributed to the increased window surface area facilitating heat transmission. The number of wings and their positions are closely related to the overall shape of the building, specifically influencing the self-shadowing effect. While their contribution remains minor compared to fixed electric heat gains, the trend observed in the previous graphs is further detailed here. An increase in the number of wings results in a decrease in window heat gains, without impacting window losses. This reduction subsequently leads to a decrease in cooling needs and the total energy demand. The relatively limited impact of these parameters on the overall results could potentially be attributed to a narrow range of variation in the shape parameters.

Furthermore, in terms of room width, it is evident that increasing room width reduces the relative significance of window gains and losses. As the width expands, the energy dependent on a fixed length of facade becomes distributed across a larger area. To determine the actual influence of thermal variation sources, it is beneficial to divide them by the functional unit related to their respective components (metres for facade and square metres for the internal gains) instead of relying solely on the raw area of the considered building wing. The following graph presents the results of this calculation.

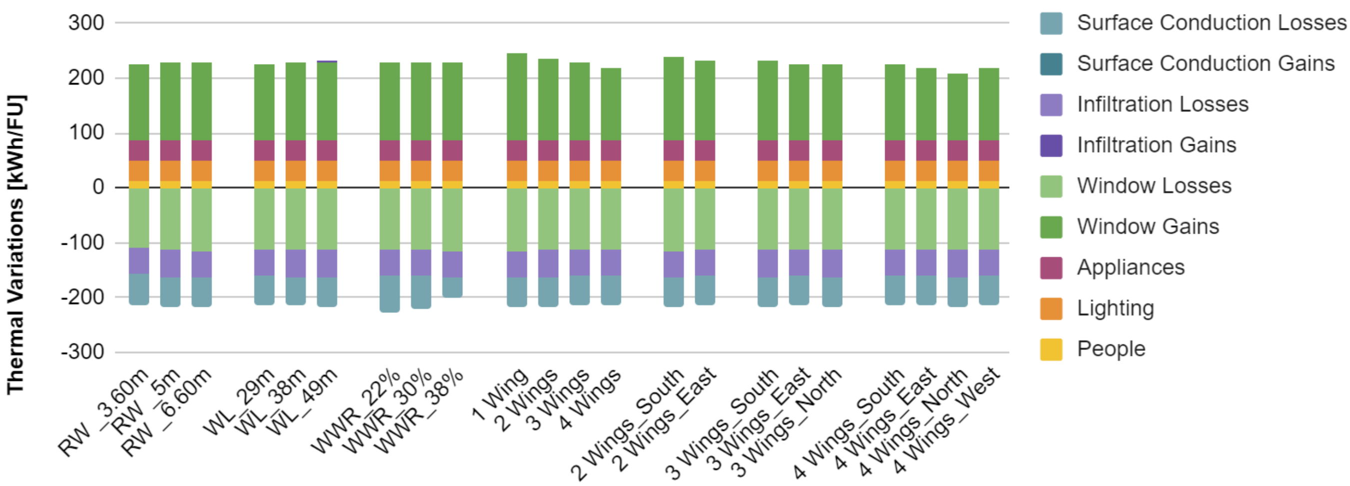


Figure 15: Annual thermal energy demand variation, by parameter and by category

The depicted graph reveals an interesting finding: the influence of the facade on the overall thermal demand exceeds that of internal sources of thermal variations within their respective functional units. Specifically, the windows have a greater impact per metre of facade compared to the electric lighting and electric appliances per square metre. This finding emphasises the significant role played by the shape of each wing and the WWR in determining the absolute thermal demands. These factors directly influence the amount of energy transmitted through the windows and the surface area over which it is distributed. However, it is important to note that the WWR primarily affects window losses, resulting in an increase in cooling needs rather than a decrease.

5.2. Lighting Results

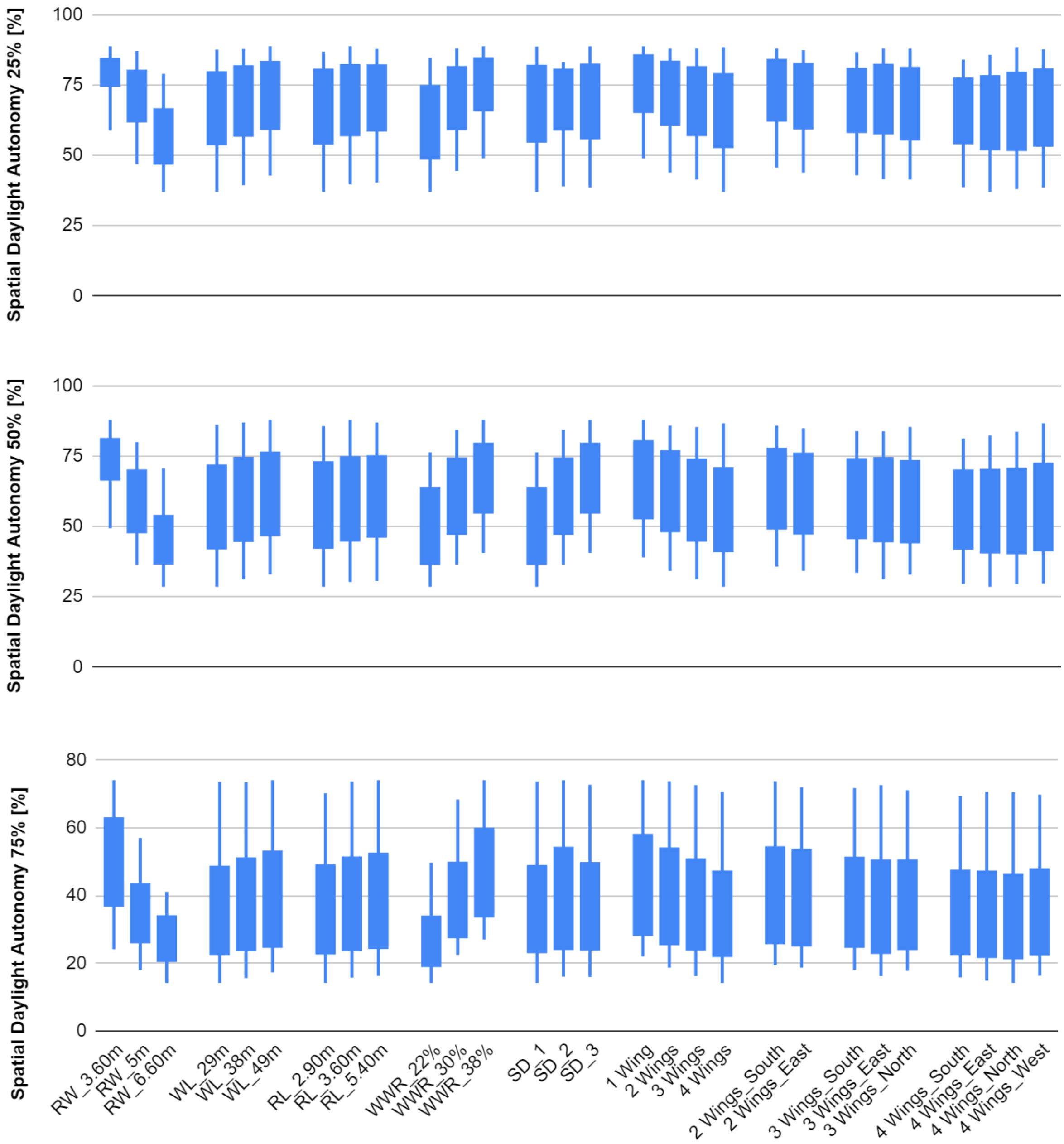


Figure 16: Spatial daylight autonomy (25%, 50% and 75%), by parameter

Figure 16 illustrates the results for the 25%, 50%, and 75% SDA for each parameter's values. It is evident that the room width and the WWR have the most pronounced influence, resulting in significantly different ranges of results across the graphs. Surprisingly, the spatial distribution only exhibits an impact on the SDA 50% graph and not on the others. However, due to the wide ranges of the results, it becomes challenging to identify clear trends. To isolate the influence of each parameter for each metric, Figure 17 depicts the average differences in the results due to changes in the specific parameter being considered.

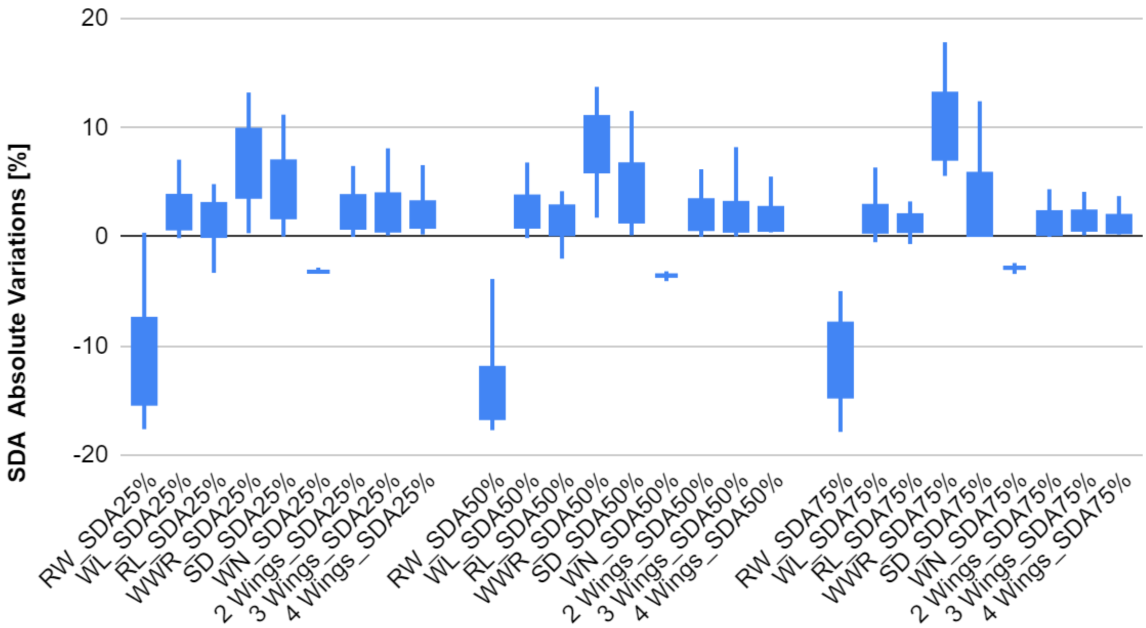


Figure 17: Spatial daylight autonomy variation, by parameter

Observing the results, it becomes apparent that the room width has the most significant influence, followed by the WWR, and then the spatial distribution. These findings align logically with the deeper a room, the more challenging it is to illuminate it solely with daylight, and the wider the windows, the more daylight it receives. The influence of the window-to-wall ratio also becomes more pronounced as the SDA percentage increases, resulting in a more uniform illumination of the room. The fact that the WWR is not the most influential parameter can be attributed to the narrow range of variation chosen for the simulations (22-38%). However, the increase in room width values falls within the minimal range prescribed by the Architects' Data [73]. This indicates that in practical terms, the room width does have a higher, but negative, influence than the WWR when the objective is to accommodate more workstations. Opting to increase the length of office rooms instead of their depth proves to be a better option for achieving adequate lighting, as it allows the designer to maintain control over the size of the windows without automatically enlarging them to maintain an acceptable level of daylight.

The influence of spatial distribution in the SDA 50% results does not stand out as prominently as it did in the general plot. However, considering that the chosen spatial distributions are relatively similar and simplistic compared to real office buildings, it is not surprising that this parameter does not exhibit significant differences in general. It can be assumed that a more diverse distribution would yield greater disparities in the results.

Parameters related to the shape of the building, such as room length, number of wings, and wing orientation, have a lesser influence on the lighting compared to other parameters. However, their influence, although not as substantial, can be attributed to the self-shadowing effect of the building. This lack of influence suggests that the range of variations for this set of parameters was too narrow, considering their relatively low impact on the thermal metrics as well. Thus, further assessment of the self-shadowing effect and its influence would be valuable, using a wider range of variations for the parameters associated with it.

5.3. Embodied Flows Results

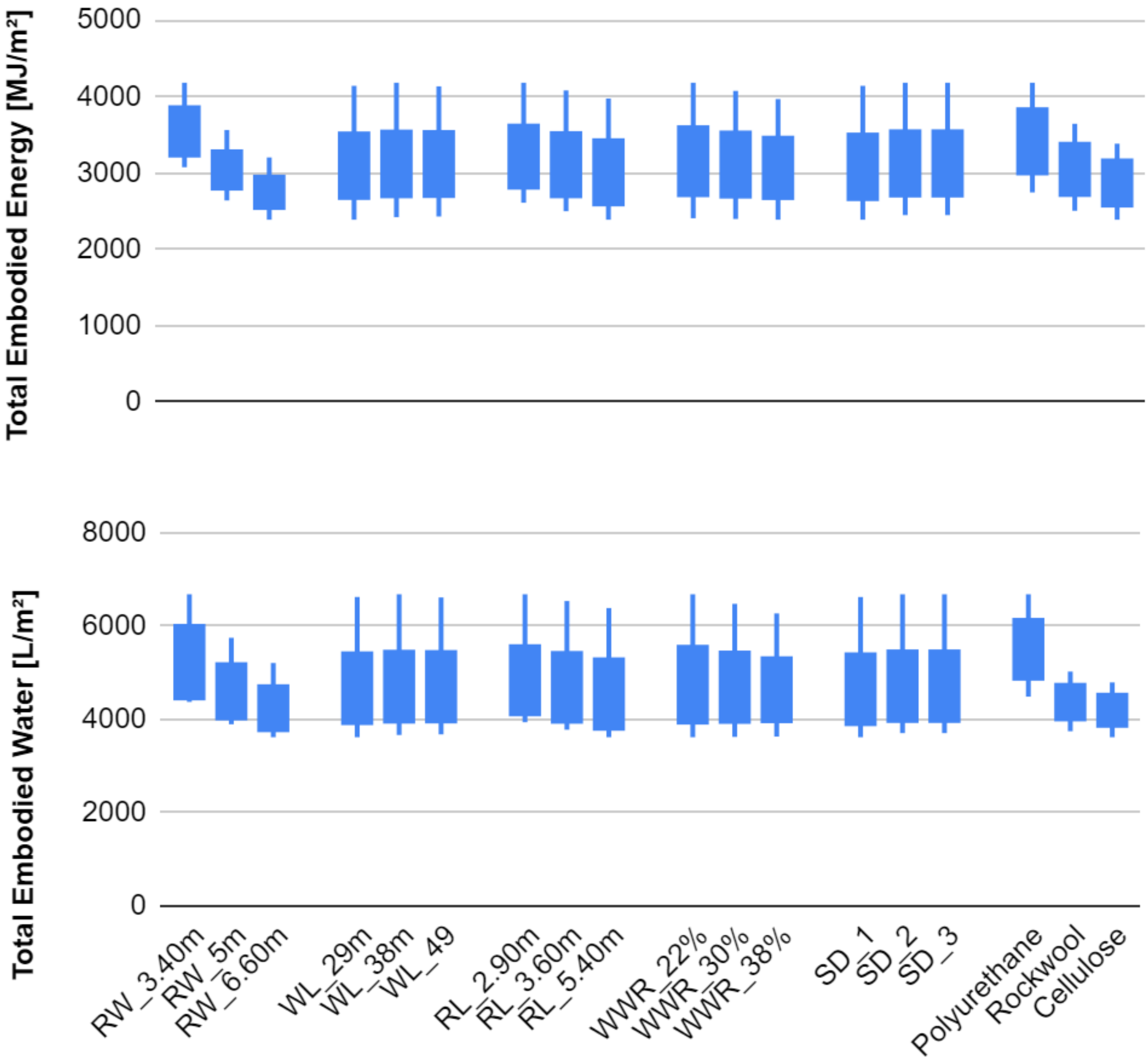


Figure 18: Life cycle embodied energy and water, by parameter

Figure 18 depicts the average results for embodied energy per square metre and embodied water per square metre across the considered parameter values. Among the parameters, two stand out prominently : room width and insulation material. The influence of room length is also noticeable, albeit to a lesser extent than the preceding parameters. To further analyse the impact of these parameters, the subsequent graph illustrates the average differences in the results attributed to variations in each parameter.

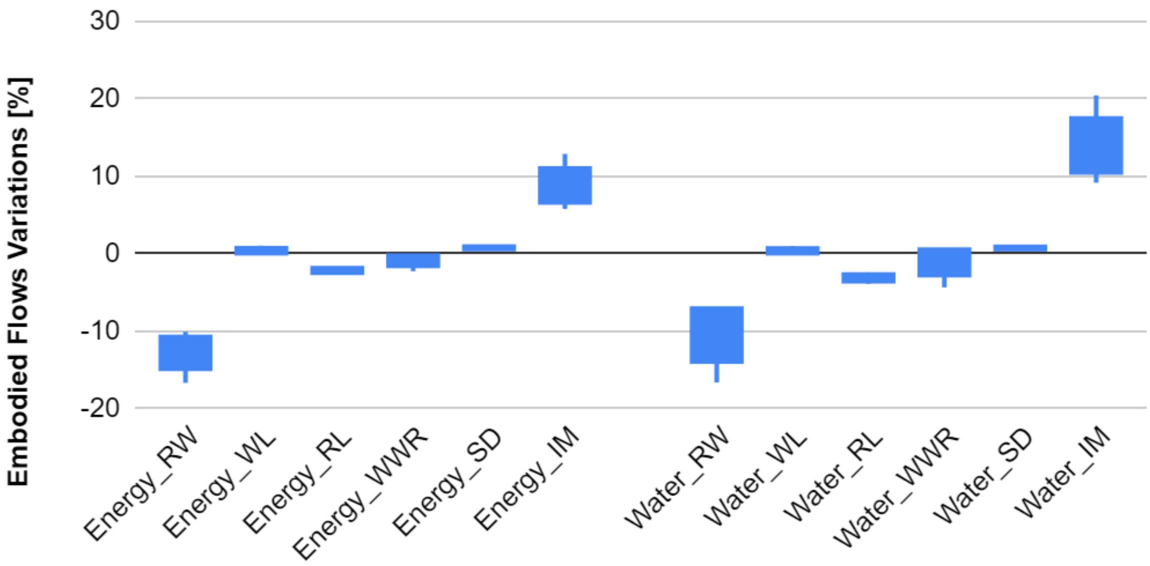


Figure 19: Life cycle embodied flows variations, by parameter

Figure 19 further validates the significance of the room width and insulation material as the two most influential parameters. While the room width demonstrates influence, the variation in wing length does not have a significant impact. This observation might suggest that floors hold greater importance than the facade. However, given that the insulation material emerges as one of the most influential parameters, it becomes necessary to disaggregate the results based on the three main modelled building components (facade, partition walls, and floors) to better understand the distribution of embodied flows. The subsequent graph presents the results of this analysis.

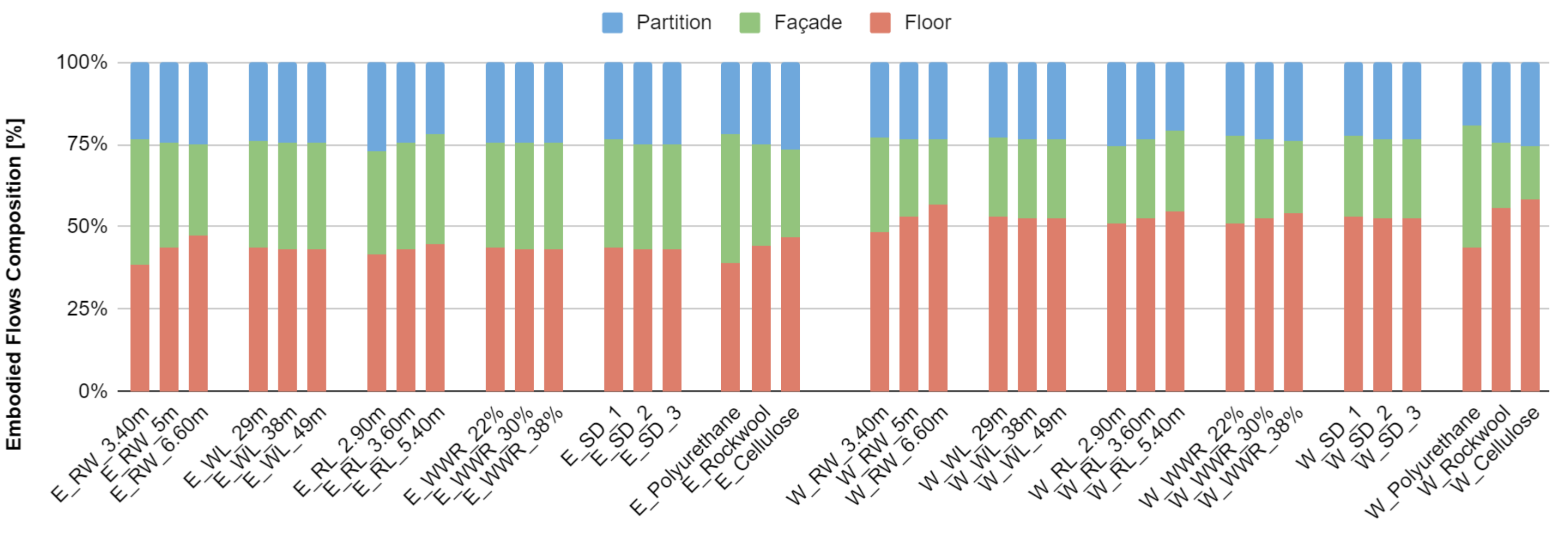


Figure 20: Life cycle embodied flows, by parameter and by building element type

Figure 20 highlights a consistent order of importance among the building elements : floors consistently exhibit the highest embodied energy and water consumption, while the facades occasionally come close in significance, and partition walls almost always demonstrate the lowest energy and water consumption. The decrease in embodied flows associated with the room length can be attributed to a reduction in the absolute volume of partition walls, resulting in a decreased relative importance of these walls in the graph. In contrast, room width does not follow the same trend but leads to an increase in the width of the wings and, consequently, the floor area. The influence of the insulation parameter is clearly visible, as cellulose insulation results in the lowest importance of the facades, while polyurethane insulation yields the highest.

5.4. Influential Parameters

Based on the observations made regarding the results of the various metrics assessed in this study, we can draw some conclusions. Each parameter exerted an influence on the system at some point. Table 11 summarises the impact of each parameter on the respective fields considered. The number, position, and length of the wings are aggregated under the 'Shape' category, as their influence is often correlated.

Table 11: Correlations between different parameters and performance metrics

Parameter	Thermal	Lighting	Embodied Flows
Window-to-Wall Ratio	Increases the cooling needs by letting more radiation enter the building without increasing the amount of heat leaving the building (greenhouse effect).	One of the two most influential parameters. Provides a more uniform illumination.	Provides no direct difference but slightly decreases the absolute insulation quantity.
Room Width	Slightly increases the total energy demands but decreases the relative importance of the window gains and losses.	Heavily decreases the spatial daylight autonomy of the area.	Increases the overall embodied flows by increasing the floor area.
Room Length	/	No significant influence.	Decreases the absolute quantity of the partition walls, thus the overall embodied flows by decreasing the density of the partitioning.
Spatial Distribution	/	No significant influence.	No significant influence.
Shape	Induces a self-shadowing effect that reduces the windows heat gains. Its influence is quite low in this study.	The self-shadowing effect is barely perceptible.	/
Insulation Material	/	/	Has a major influence in the overall embodied flows. The polyurethane is the material leading to the highest embodied flows while the cellulose leads to the lowest.

Based on these findings, it is evident that the WWR, room width, and building shape play significant roles in influencing the overall environmental performance and daylight autonomy of a building. Therefore, careful consideration and control of these parameters during the design process are crucial.

Considering the observed trends, it is recommended to maintain a compact building shape by opting for shorter wing lengths and a closed configuration to maximise the self-shadowing effect. However, the room width should be minimised for lighting purposes. In this context, it also affects the width of the entire wing due to the considered spatial distributions. It is advisable to employ a spatial distribution that includes a central row between the office room rows, as this would reduce the overall thermal energy demands per square metre of the building. Increasing the building density to reduce embodied flows is achievable by employing a higher room length, as its influence on the thermal and lighting aspects is negligible.

Regarding the WWR, it should be determined based on the desired internal daylight autonomy, considering both the shadow cast by the surrounding context and the building itself. In general, wider windows slightly decrease the absolute insulation quantity and, consequently, the total embodied energy of the building. Additionally, since the office program often requires a significant amount of cooling energy, incorporating large openings in the facade areas that are frequently shaded by the context can greatly enhance daylight penetration.

To validate these assumptions, the scenarios corresponding to these design guidelines are highlighted in the global parallel coordinates plot presented in Figure 21.

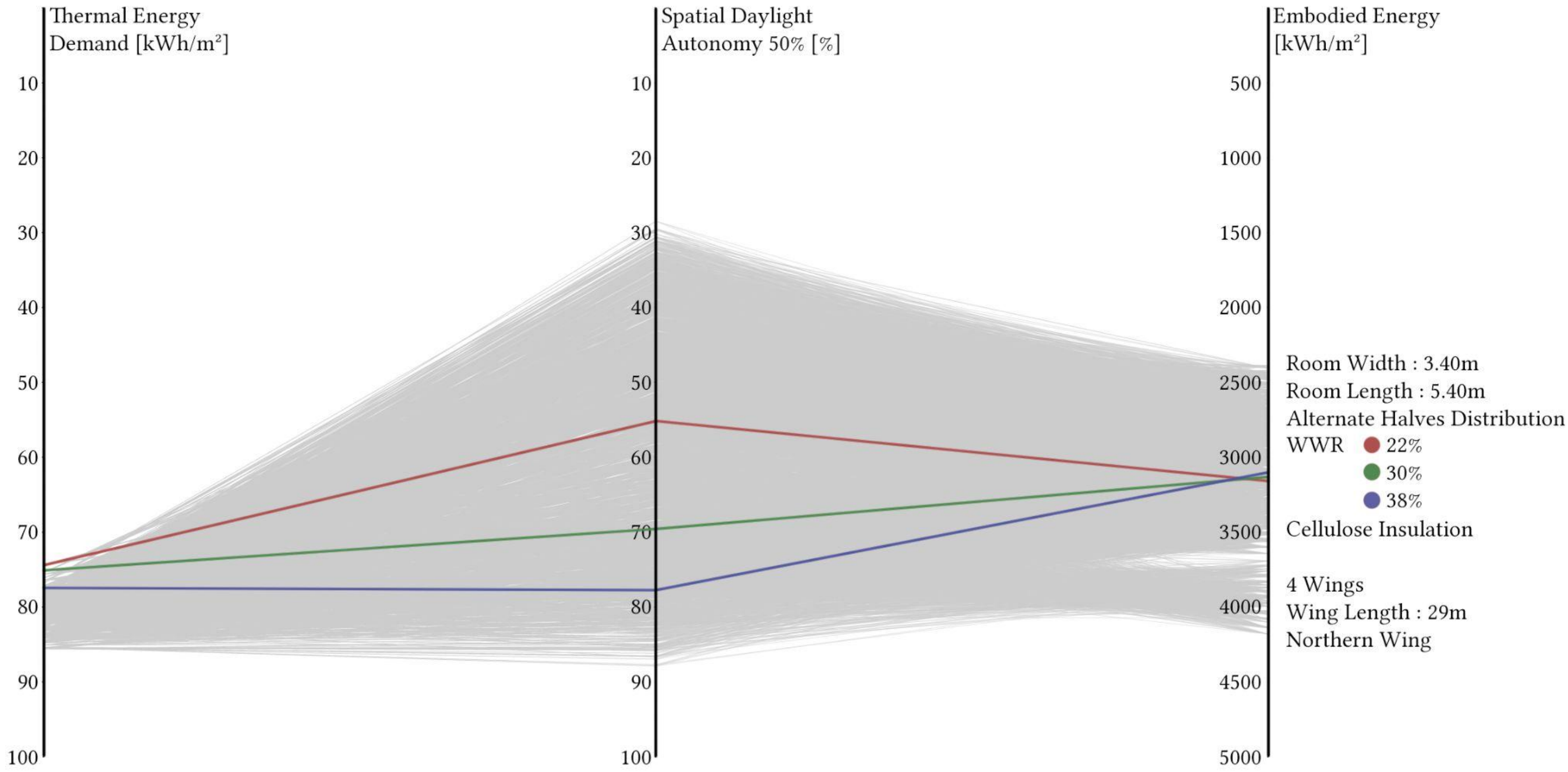


Figure 21: Parallel coordinates plot plotting the linkages between thermal energy demand, spatial daylight autonomy (50%) and embodied energy.

The highlighted scenarios in the global parallel coordinates plot demonstrate that the selected values actually yield the lowest thermal energy demands while ensuring an acceptable level of daylight and a moderate embodied energy. While the WWR values lead to significant variations in the SDA 50% results, their impact on the energy metrics is comparatively minor. Therefore, opting for the highest wwr value seems to be the optimal solution to achieve an environmentally efficient building while preserving occupant comfort.

In a case where the embodied energy needs to be minimised, the room width must be increased. The following figure illustrates this case by fixing the WWR to its highest value and highlighting the scenarios for which only the room width varies.

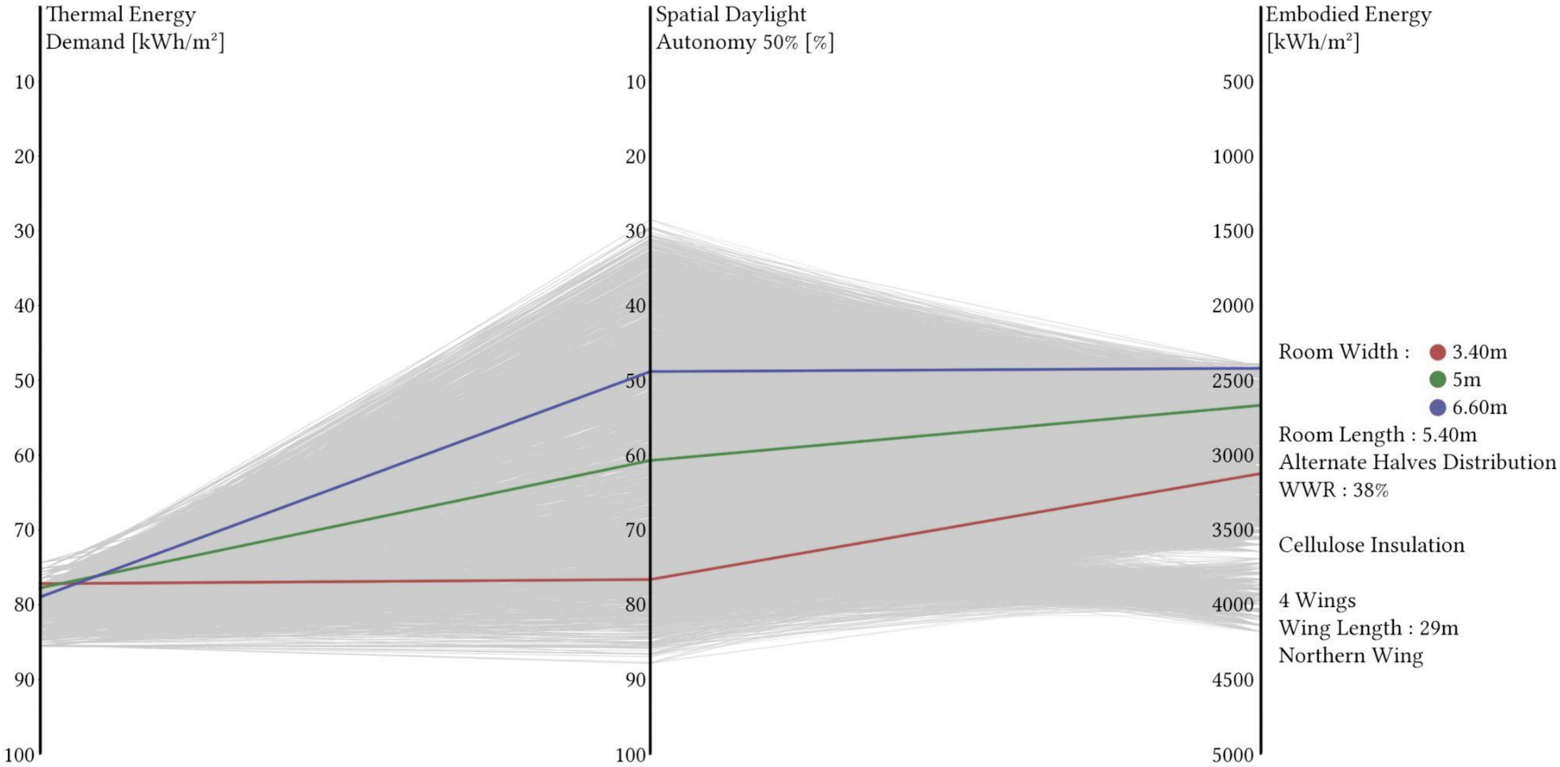


Figure 22: Parallel coordinates plot plotting the linkages between thermal energy demand, spatial daylight autonomy (50%) and embodied energy.

We observe that the embodied flows are indeed more influenced by the width of the wings than by the WWR. The room width then ties the embodied flows and the lighting together and prevents the improvement of one without degrading the other. However, as proven in countless studies, the operational flows still have a greater importance in the life cycle flows of a building than the embodied flows. Thus, a minimal room width is still preferable to a minimal embodied energy in this case.

6. Discussion

6.1. Comparison to the literature

The study conducted by Gauch et al. in 2023 [23] is the closest in terms of aim and methodology to this thesis. They explored a wider range of parameters but focused on embodied and operational flows, excluding lighting. Their results led to several interesting conclusions. Our findings align with theirs in that the WWR and building shape have a significant impact on all the aspects studied. However, Gauch et al. 2023 [23] concluded that a compact building with a low WWR is beneficial in terms of both embodied and operational flows. We reach the same conclusions, however we are able to balance those conclusions with the daylight results we obtain. We find that increasing the width impacts significantly the daylight comfort of the occupants by drastically decreasing the SDA of the wing. In fact, the decrease of SDA appears to be relatively more impactful than the increase in embodied and operational energy. This conclusion also applies to the WWR as its influence on the operational and embodied flows is significantly lower than its influence on the daylight autonomy. Moreover, the spatial distribution of the rooms appears to have a substantial influence on the lighting as well and should not be excluded from such analysis, which is supported by the review of Du et al. 2020 [20].

Hasik et al. 2019 [27] is another study we encountered that considers shape parameters in the life cycle assessment (LCA) of office building scenarios. Their conclusions support those of Gauch et al. 2023 [23] and our own findings regarding the influence of building aspect ratio and WWR on life cycle flows. However, they identified that the number of stories is actually more influential than the WWR and the shape. This parameter was not specifically considered in Gauch et al.'s study [23] or in ours, highlighting the importance of including it in future research in this field.

From a broader perspective, parameters related to early design decisions, such as shape and WWR, have a substantial influence. Azzouz et al.'s study in 2017 [10] delved into more detailed construction aspects than our research but also found that decisions made during the early design stages have the most significant impact on the overall LCA of office buildings.

On the other hand, after comparing the thermal results to those of the benchmark office buildings referenced in the paper of Schlegl et al. 2019 [54], significant differences arise. Their cooling loads are higher than their heating loads, but the proportion is not as marked as in our results. Thus, we checked the calculation details of the Energy Plus reports, and identified that the default values referenced in the Honeybee component for the ventilation system were not taken into account by the simulation engine. This issue in the code explains the significant amount of cooling energy demand as the air could not escape the wings. However, as the aim of this study is to evaluate the variations in the results instead of their absolute values, it is possible that this issue does not influence the conclusions in a significant way. This is corroborated by the similarities between our conclusions and those of other studies referenced above. This issue will be fixed between the submission of this thesis and its oral defence, and an erratum to this document will be attached.

6.2. Limitations

6.2.1. Scope

In this study, due to computational limitations, the number of variations for each parameter had to be reduced, which means that the full influence of the parameters could not be fully explored. One parameter that would benefit from an expanded range of variations is the WWR). Extending the range of WWR values in both directions would provide a more comprehensive understanding of its impact on the studied metrics.

The shape of the building encompasses multiple parameters, each with its own range of variation. While the self-shadowing effect of a building was found to have some influence, it was not as significant compared to other parameters. Increasing the compactness of the building by using lower values for wing lengths and higher values for width could address this issue. Additionally, the number of stories in the building and the altitude of the studied floor within the building could also have a significant impact on the self-shadowing effect and should be considered for future research.

Furthermore, the spatial distribution of the office rooms in this study was kept very similar across scenarios, resulting in a minimal influence on the considered metrics. Exploring a more diverse range of spatial distributions could unveil previously unknown energy and lighting trends associated with this parameter.

6.2.2. Tools

The methodology was divided in 3 major phases: the modelling of the scenarios with Rhino Grasshopper, simulations conducted on the modelled scenarios using Ladybug Honeybee and EPiC Grasshopper, and a statistical analysis of the results via Python.

Python was chosen for the statistical analysis phase due to its widespread use and efficiency in handling data sets. However, it is suggested that Python could also be used for the modelling phase instead of Grasshopper. Grasshopper is a visual programming environment that excels in manipulating geometric data, assembling complex geometries, and real-time visualisation in the Rhino 3D environment. While Grasshopper is efficient for these tasks, it can encounter limitations in managing large amounts of data and RAM resources. To overcome this limitation, careful algorithm planning and optimization of geometric data management could be implemented in Grasshopper. Another alternative is to use Python either in combination with Grasshopper through the Python library embedded in Grasshopper or by directly defining geometric data in Python. Androzics-Zetz et al. 2022 [7] take a step in this direction by developing a geometry generation process entirely in Python.

Regarding Ladybug Honeybee, it is a valuable tool suite that establishes effective connections between the Grasshopper environment and simulation engines. However, the suite is currently undergoing a rewriting process, which has left some old components without equivalents in the newer versions. This required the use of an older version of Ladybug Honeybee, which may introduce compatibility issues with the simulation engines. If Python is used for the modelling phase, it is suggested to directly interact with the simulation engines instead of relying on the Ladybug suite for interactions, as this can help overcome potential compatibility issues and streamline the process.

Overall, considering the use of Python for both the modelling and statistical analysis phases, optimising data management in Grasshopper, and exploring direct interaction with simulation engines can enhance the efficiency and compatibility of the methodology.

6.2.3. Simulation results

In the thermal simulations, the static nature of the lighting contribution poses a limitation on the validity of the results. To address this limitation, establishing a bridge between the lighting and thermal simulations is recommended. This can be achieved by analysing the Spatial Daylight Autonomy (SDA) results on an hourly basis to determine the periods throughout the year when electric lighting would be required. These ranges of hours can then be incorporated into the EnergyPlus engine to obtain more accurate thermal simulation results for each scenario. This approach can help improve the assessment of the influence of parameters on the thermal behaviour of the building without significantly increasing computation time.

Regarding the lighting simulations, a reduction in the number of ambient bounces from two to one was made, but it did not appear to have a significant impact on the results. However, conducting a sensitivity analysis to evaluate the influence of a lighting simulation with two ambient bounces is recommended to verify this assumption.

The data used for the computation of embodied flows in the scenarios is sourced from the EPiC database [70], which employs Australian coefficients for converting material quantities into embodied energy and water, as well as the Australian energy mix for converting embodied energy into embodied greenhouse gas (GHG) emissions. Since the energy mix differs between Australia and Belgium, embodied GHG emissions were not considered in the analyses. However, variations in material production processes between regions could affect the coefficients used for conversion. Conducting a sensitivity analysis by utilising another database to assess the potential influence on the results is advisable.

In terms of the assemblies used for calculation, the floors were modelled as simple concrete slabs. Considering the significant impact of floors on the final results (Stephan et al. 2017) [56], providing a more detailed composition of the floors would enhance result accuracy and reliability.

6.3. Contributions

While there have been numerous studies evaluating the operational and embodied flows of office buildings, fewer studies have focused on assessing the influence of parameters on these environmental flows. This study is novel as it evaluates the influence of a set of geometric parameters on both the lighting and thermal aspects of office buildings within the same framework. The findings highlight the importance of considering thermal and lighting analyses together, as their results are closely interconnected and mutually influential.

Furthermore, this study is one of the first to incorporate architectural parameters in the analyses. It includes parameters related to the building shape as well as internal layout configurations. These parameters were found to have a significant impact on the overall environmental flows of the buildings, although their range of variation in this study was limited. This opens up new avenues for future research, enabling a more comprehensive exploration of the boundaries and implications of these influential architectural parameters. This, in turn, can contribute to providing more realistic and practical recommendations for practitioners in the field.

Lastly, the research methodology employed in this study allowed for a simple yet systematic evaluation of the parameter influence. The insights gained from this study provide valuable guidance on enhancing the efficiency of this methodology and facilitating easier comparisons of analysis results across different fields. This contributes to the advancement of research methods and promotes better understanding and decision-making in the design and evaluation of office buildings.

7. Conclusion

In this study, the objective was to fill a knowledge gap by evaluating the performance of office building scenarios in terms of energy and lighting metrics while varying shape-related parameters. A total of 7290 theoretical office building floors were generated in Rhino Grasshopper by combining eight different parameters. These scenarios underwent thermal and daylight simulations, as well as an evaluation of embodied flows. The results were then analysed to assess the influence of each parameter on the overall system for each metric.

The findings indicate that the most influential parameters are the width of the rooms (which also determines the width of the building wings), the window-to-wall ratio (wwr), the insulation material, and to a lesser extent, the shape of the building. Among these parameters, room width and wwr had a clear influence on every considered metric. Lighting performance was particularly sensitive to their influence and should be carefully controlled during the design process. The choice of insulation material also had a significant impact on embodied flows, although floors accounted for the largest share of the total embodied energy in each scenario. However, the embodied flows evaluation used a simplistic approach for modelling the floors, and a more accurate modelling approach could affect their share. The shape parameters were found to have an influence on the results, albeit a minor one. Their main influence appeared to be the self-shadowing effect they induced. However, the range of parameter variations applied to shape-related parameters may have been too narrow to fully explore their influence, suggesting that a wider range of variation specifically focused on the shadowing effect should be considered in future research.

Based on these results, practitioners should consider narrower wings and carefully control the shape of office building projects to provide shading to the facade and limit overheating in internal spaces. This allows for effective heat dissipation from the numerous appliances typically present in office buildings through natural ventilation, while maintaining acceptable daylight autonomy in work areas. These recommendations, based on the initial findings of this study, require further research to consolidate and evaluate the full range of influence of the promising parameters identified.

In terms of general thermal energy results, it was found that heat gains from electric appliances and electric lighting constituted the largest absolute share of total temperature variations. However, when normalised by their own functional unit, these heat gains were smaller than the temperature variations caused by the facade. The fixed nature of electric lighting and appliances in the calculations represents a limitation to the accuracy of the results. Future research should focus on bridging the gap between thermal and lighting simulations to obtain more accurate estimations of electric lighting needs.

In conclusion, the methodology developed in this study successfully balanced energy-related and lighting comfort results, providing a more comprehensive view of the situation. As the first application of this methodology to office buildings, there is still ample room for improvement and streamlining of the process. Developing a Python workflow to distance the study from Grasshopper appears to be the next step in refining this methodology for larger datasets and expanding its applicability.

8. List of Figures

9. List of Tables

10. References

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