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Towards a parametric early design approach for office buildings that integrates life cycle assessment and indoor environmental quality

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A R T I C L E I N F O

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A B S T R A C T

The construction sector is responsible for significant greenhouse gas emissions and therefore is a major driver of climate change. We must adapt our practices to design buildings that aim to achieve climate neutrality. The early design stages are critical to achieving this objective as most impactful decisions are made then. Yet very little data on the building design are available at early design. In parallel, the current research on life cycle greenhouse gas emissions has focused more on residential than office buildings. Furthermore, existing life cycle assessment studies of buildings frequently exclude lighting comfort from their scope. In this study, we propose a parametric approach to quantify the influence of design parameters on the life cycle energy use and greenhouse gas emissions, as well as lighting comfort. This approach is based on the generation of office layout models. Embodied flows calculations and energy and daylight simulations are then conducted on the generated models to evaluate their performance across two main dimensions: life cycle greenhouse gasses emissions and spatial daylight autonomy. Lastly, a sensitivity analysis quantifies the individual influence of the design parameters on these dimensions. We find that geometry has a significant influence on the performance of the models. In fact, we found that the width of the building and subsequently its density are the most influential parameter, followed by the window-to-wall ratio. Using parametric models at the early stage of design can help identify design solutions that achieve a high life cycle environmental performance, helping stir the construction sector towards climate neutrality while maintaining comfort standards.

1. Introduction

Our climate is changing at an alarming pace. One of the main causes being the greenhouse gasses (GHG) emitted by human activities [1]. The Paris Agreement [2] aims to limit the temperature rise to 1.5 °C by 2050, and 2 °C by 2100. The construction sector is critical for achieving this aim, as its operation alone accounts for around 40 % of GHG emissions in Europe [3].

To reduce the environmental effects of buildings, it is critical to understand their environmental performance. Life cycle assessment (LCA) is the most advanced method to quantify the potential environmental effects of a building [4]. This method is enshrined in the ISO 14, 044 [5] and ISO 14,040 [6] standards. The EN15978 [7] focuses on the LCA of buildings and divides the life cycle of a building in four main stages: production of the materials and construction of the building (stage A), operation of the building (stage B), end of life of the building (stage C), and benefits and loads beyond the primary life cycle (stage D). Currently, many studies limit their evaluation to the energy use during the operation phase, in line with policies that focus on the effects related to building use [8]. However, as increased energy efficiency reduces operational effects, the embodied environmental effects associated with material manufacturing and building maintenance increase over the life cycle of a building [9–12]. Moreover, recent studies established that nearly zero energy buildings (NZEB) might paradoxically result in an increased total life cycle energy use due to their additional embodied energy [13].

To date, not all building types have been covered equally using LCA. Zaker Esteghamati et al. [14] observed that the LCA literature on office buildings is scarce compared to the one on residential buildings. Importantly, they found that it is difficult to compare LCA studies on office buildings as these studies often disregard several life cycle stages or lack a sensitivity analysis step in their method.

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Even when LCA is used to inform life cycle environmental performance, it still suffers from certain limitations. Firstly, LCA is currently often used too late in the design process [15,16] although the most influential decisions are made during the early design stages [14,17]. Secondly, the study by Jusselme et al. [18] reveals that one of the limitations to the application of LCA in practice is the resource intensiveness of current approaches. They advise for a more parametric approach. However, a recent study revealed that the design variables considered as highly influential in the literature do not always match those identified by building designers [19]. In fact, the latter identify the number of storeys and the storey height, among others, as being critical. These parameters relate to the geometry of a building, which is rarely studied but is significant as noted by Jusselme et al. [20], Kistelegdi et al. [21] and Latha et al. [22]. As such, there is a need for early-stage parametric LCA of buildings which include geometry and other influential parameters that drive building design.

In parallel, it is also important to assess the comfort of the building users. Thermal and visual comfort metrics are still rarely taken into account in studies that research the design of buildings [21]. Shahbazi et al. [23] advocates to systematically include daylight metrics as balancing factors for energy studies. Thus, the LCA approach proposed above needs to be coupled with an assessment of the thermal and visual comfort of users.

A parametric approach can be highly beneficial to conduct an integrated LCA and comfort analysis of a building. Parametrisation in LCA not only provides detailed data on material quantities for compiling life cycle inventories, but it also overcomes limitations of time-consuming and data-intensive modelling processes [24]. Parametric approaches in building LCA designate a wide spectrum of approaches [18,19,25,26]. In this study, we define a parametric approach as a modelling method based on the definition of a limited set of base parameters, articulated through explicit rules, to generate a range of design or performance variants. It can be applied to any modelling workflow – including geometric design, environmental impact (LCA), or comfort assessment – and supports sensitivity analysis and optimisation. While most modelling tools, BIM tools included, allow some degree of parametrisation, fully parametric workflows are typically enabled by visual programming environments such as Grasshopper or Dynamo, which facilitate flexible and automated exploration of design alternatives. Combining a parametric approach with LCA represents a valuable opportunity to identify the design parameters that significantly influence the life cycle environmental performance of buildings.

1.1. Aim and scope

The aim of this paper is to develop a parametric LCA workflow for the early-design stages of office buildings. This workflow must enable the evaluation of both embodied and operational greenhouse gas (GHG) emissions as well as daylight autonomy across a set of parametrically derived design options.

The study focuses on calculating GHG emissions with characterisation coefficients for operational energy demand and construction materials. GHG emissions are considered due to their direct link to climate change through their contribution to global warming potential. In addition, daylight autonomy is included in the workflow because of its importance on mental and physical well-being, particularly in offices [27]. Thermal comfort was excluded due to limitations on the scope, this is further discussed in Section 5.3.

Embodied energy and greenhouse gas emissions, operational energy use, and spatial daylight autonomy are monitored in this study. The case study location is set to Brussels, Belgium where local climatic data are used for thermal simulations and ensure contextual relevance of the findings.

The stages included in this study are highlighted in Fig. 1, which comes from the EN15643 [28]. The EN15643 completes the EN15978 [7] by adding the A0, B8 and D1 and 2 stages.

The use phase is included via the heating and cooling energy use (B6). Electricity needed for appliances and lights, and energy needed for domestic hot water are excluded. The period of analysis considered is 60 years, in line with the Belgian tool for the LCA of buildings, TOTEM [29]. The replacement of interior finishes (B4) is included. Cost and social effects considerations are out of the scope of this study and could be included in future research.

1.2. Structure

The structure of this paper includes 6 sections. Section 2 summarises the existing literature. Section 0 describes the method used. Section 4 provides the results obtained. Section 5 and 6 discuss and conclude this paper, respectively.

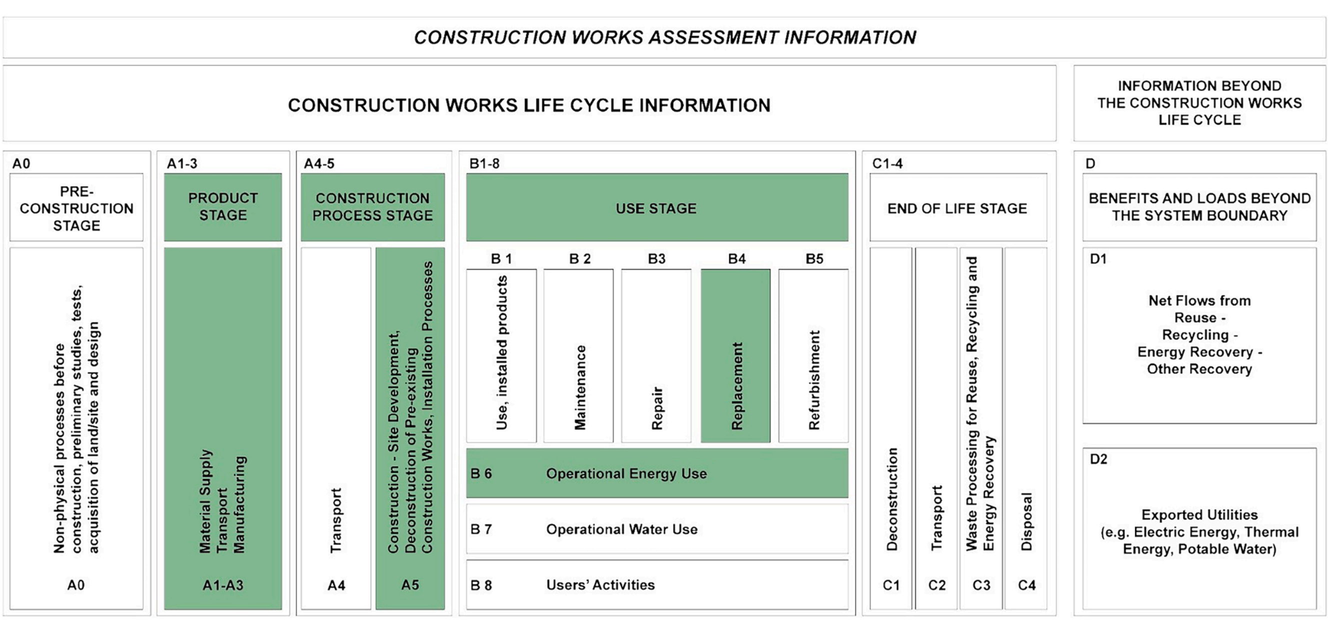

Fig. 1. Life cycle stages included in the scope of the study, according to the EN15643.

2. Existing studies on the life cycle assessment of office buildings

A scoping literature review was conducted using Scopus and led to the identification of 32 studies published between 2012 and 2023 that performed a LCA on mid-rise office buildings. We extracted six data types from each paper to address the aim of this paper, namely: (1) the modelling approach employed, (2) the focus of the study, (3) the assessment period, (4) the LCA stages considered, (5) whether the study considers daylight comfort or not, (6) and the parameters varied when relevant.

The modelling approach is divided in three categories:

- case study of an existing building;
- case study of an existing building that has been parametrised to explore alternatives to the base case; and
- theoretical models generated by combining design parameters.

The focus column reports the building components on which the parametric study is focusing. The parameters columns provide insights on whether the study only considers parameters within its focus, or beyond.

Table 1 presents methodological choices made in the analysed sample of studies. We observe that most studies include several life cycle stages in their scope. However, a more detailed examination of the studies reveals that the stages included are rarely complete. Most studies include stages A1–3 (88 %), less include A4–5 (69 %), and only 38 % consider B4 in their scope. 80 % of the studies cover B6 and 54 % cover C1–4 stages. Out of the 26 studies reviewed, only 4 cover stages A1–5, B4 and 6, and C1–4.

In this sample, 20 out of 26 papers are based on case studies, 13 of which explore alternatives to the base cases. In total, 19 out of 26 studies involve parameters in their methodological approach. Most of these parametric studies focus on evaluating building components and systems. Only two papers assess the sensitivity of the environmental performance of the building to its geometry, and none of them considers the internal layout of the building. Finally, two papers include both energy and daylight autonomy in their assessment scope.

The findings of this literature review highlight the need to include geometric variables in the scope of parametric studies. It additionally reveals a lack of studies that consider the lighting comfort of the users alongside energy and environmental performance of the building.

Several tools support the generation of design variants and the assessment of environmental impacts and occupant comfort. Grasshopper [54], a visual programming environment integrated with Rhino [55], enables parametric modelling and connects to simulation tools and databases through plugins. For instance, Honeybee links Grasshopper with EnergyPlus [56] and Radiance [57] to perform energy and comfort simulations, while EPiC Grasshopper [58] enables embodied impact calculations based on hybrid life cycle inventory data. On the other hand, Revit [59] is a Building Information Modelling (BIM) software that is complemented by several tools to make the most out of the profusion of data sourced from its BIM nature. Similarly to Grasshopper, Dynamo for Revit [60] supports parametric workflows within a BIM environment, particularly for geometry generation and automation. Sefaira [61] is a third-party tool that integrates with both Revit and Sketchup [62]. It enables the assessment of operational energy and daylight autonomy metrics. However, it allows for less control over simulation parameters compared to its Grasshopper counterpart, Honeybee. Autodesk Forma [63] is a standalone software focused on early-design explorations with a simplified exportation pipeline to Revit. Forma provides predictions for both daylight potential and embodied greenhouse gas emissions via the EHDD C.Scale API [64], using AI models based on geometric and usage parameters. This approach aligns closely with the objectives of this study but it does not include internal layout parametrisation or hybrid life cycle inventory data, which can enhance result accuracy. Being anterior to Revit in its workflow, it also hinders the parametric capabilities of Dynamo. Lastly, Laiout [65] uses AI to generate office floorplans from manually defined zones and boundaries and supports flexible layouts, but does not rely on parametric rules nor integrate environmental or comfort metrics, limiting its use for optimisation. Following these observations, Grasshopper is found to be the most suitable option to achieve the goals of this study due to the comprehensiveness and ease of use of its environment.(Fig. 2).

3. Method

The overall research approach employed in this study consists of three main steps. Firstly, a collection of office building geometries are modelled in Grasshopper using a set of geometric parameters. These geometries are based on good design practices mentioned in the latest version of the handbook of Ernst Neufert: Architects Data [66]. Secondly, the office building variants generated undergo three types of analysis: a daylight simulation, an energy simulation, and an embodied environmental flows calculation. The metrics assessed via these analyses are: Spatial Daylight Autonomy (SDA) and life cycle (LC) GHG emissions. The choice of SDA to assess the lighting comfort of the office users is motivated by its human-centric nature: it provides a rational base on which compare the sufficiency of daylight to perform office tasks. LC GHG emissions are calculated by adding the calculated embodied GHG emissions and the operational GHG emissions. Thirdly, a sensitivity analysis is applied to the results of the simulations and calculations to evaluate the influence of each generative parameter on the results of the simulations and calculations.

3.1. Generating building design variants

The first step consists in defining the parameters employed to represent a theoretical building. The value taken by each parameter can vary within a range. A set of rules is defined to both limit the range of variation of each parameter and describe how to combine the parameters to model a building. A building scenario designates here a unique combination of the values of the parameters. The database of scenarios generated in this study contains all the possible combinations of the values of the parameters defined below.

The floor plan of the building is composed of simple parallelepipeds (wings) containing office spaces, framed by service blocks containing vertical circulation, sanitary facilities, and maintenance storage spaces. Two atria are separated by a central wing, which is the subject of the analyses performed. This shape enables to account for the shadow cast by the surrounding context and by the rest of the building itself. Fig. 3 describes the floor plan envisioned. The dimensions of the wings are governed by the dimensions of the rooms, considering a length of eight rooms. The height of the building was chosen to fit the height of a mid-rise office building as defined in Architect's Data [66]. The height of the floors is fixed to 3.70 m based on the recommendations for office floors that need to accommodate heating water pipes and electrical cables in the rooms, and ventilation ducts in the corridor.

Within the floor modelled, the layout of the partition walls is parametrised. We define three possible layouts based on recommendations in the Architect's Data [66] of leaving half of the floor area free to be arranged by the tenant of the building. The width of the circulation was set to two meters. Additionally, one meeting room is defined in each wing, taking up the space of two office rooms. These layouts are illustrated in Fig. 4.

The last set of parameters defines the size of the office rooms. The Architect's Data defines a generic functional office room layout [66] that is parametrised and used to populate the wings. Fig. 5 shows the layout in question and its decomposition in parameters.

Finally, openings are ruled by the Window-to-Wall ratio (WWR). The windows are evenly distributed across the façade to have one window per room (two for the meeting room), located at the centre of the façade

Table 1
Scoping review of existing studies on the parametric life cycle assessment of mid-rise office buildings.

Reference	Modelling Approach			Focus	Assessment Period [Years]	LCA Stages					Daylight Comfort Considered	Parameters							
	Case Studies	Case Studies + Variations	Theoretical Scenarios			Production A1-A3	Construction A4-A5	Replacement B4	Operation B6	End of Life C1–4		Shape	Internal Layout	Structure	Envelope	Construction System	Renewable Energy Systems	HVAC System	Usage
Ajayi et al., 2019 [30]		×		Energy	30	×	×	×	×	×						×			
Alshamrani, 2016 [31]		×		Structure & Envelope	60	×	×	×	×	×				×	×	×			
Amiri Rad and Fallahi, 2019 [32]		×		Envelope	10	×			×						×				
Asdrubali et al., 2013 [33]	×					×	×		×	×									
Azari, 2014 [34]			×	Envelope	60	×	×	×	×						×				
Biswas, 2014 [35]	×				50	×	×		×										
Gangolells et al., 2020 [36]		×		Renovation	50	×	×	×	×	×									
Garcez et al., 2018 [37]		×		Structure	50	×	×			×				×					
Gauch et al., 2023 [38]			×	Energy	1	×	×		×			×		×	×				×
Hasik et al., 2019 [39]			×	Energy	60	×		×	×			×		×	×		×		
Larivière-Lajoie et al., 2022 [40]		×		Envelope	50	×	×		×	×					×				
Luo, 2022 [41]		×		Renovation	50	×	×		×	×					×		×		
Marino et al., 2017 [42]			×	Energy	1				×						×				
Marique and Rossi, 2018 [43]	×				50	×	×		×	×									
Méndez Echenagucia et al., 2015 [44]			×	Energy	1				×						×				
Moschetti et al., 2019 [45]		×		Energy	60	×		×	×							×	×		
Najjar et al., 2017 [46]	×				50	×		×		×									
Peng, 2016 [47]	×				50	×	×		×	×									
Robertson et al., 2012 [48]		×		Structure & Envelope	50	×	×							×	×				
Shahbazi et al., 2019 [23]		×		Lighting	1				×		×				×				
Taborianski and Prado, 2012 [49]			×	Envelope	60	×	×		×	×					×				

(*continued on next page*)

Table 1 (*continued*)

Reference	Modelling Approach			Focus	Assessment Period [Years]	LCA Stages					Daylight Comfort Considered	Parameters							
	Case Studies	Case Studies + Variations	Theoretical Scenarios			Production A1-A3	Construction A4-A5	Replacement B4	Operation B6	End of Life C1–4		Shape	Internal Layout	Structure	Envelope	Construction System	Renewable Energy Systems	HVAC System	Usage
Tevis et al., 2019 [50]		×		Energy	50	×	×	×	×	×							×		
Thiel et al., 2013 [51]	×				NA	×	×												
Victoria and Perera, 2018 [52]	×				NA	×													
Wu et al., 2012 [53]		×			50	×	×		×	×						×			
Zaker Esteghamati et al., 2022 [14]		×		Energy	50	×	×	×	×	×						×			

wall of the room. Each window runs from 1.20 m above the floor to 50 cm below the ceiling to leave space for radiators, cables, and heating water pipes [66], their width is governed by the WWR. The WWR can take three values, which were selected according to the findings of Goia, and Ma et al. [67,68], i.e. 30 %, 40 % and 50 %.

Grasshopper was selected to assemble the aforementioned parameters and generate a three-dimensional representation of a building. This plugin of Rhino 3D was selected due to its compatibility with several calculation and simulation engines required for the second step of this approach, detailed in Section 3.2. Only one floor is modelled accurately to reduce computation time to reasonable extents. This floor is the third of the five storeys. The rest of the building is kept as a volume to include shadowing effect. The Grasshopper algorithm developed for the generation and analysis of the models is illustrated in

Fig. 6 and the file is provided in the supplementary materials.

3.2. *Analysing the building design variants*

This study aims to quantify both life cycle energy and embodied greenhouse gas emissions of offices, and the comfort of their users. Therefore, three types of analysis are conducted on each building design generated: an embodied energy and greenhouse gas emissions calculation, an operational energy simulation, and a daylight simulation.

Embodied energy and greenhouse gas emissions calculations are conducted in two steps. Firstly, a Bill of Quantities (BoQ) of the materials present in the studied floor is established. Secondly, these quantities are converted to embodied environmental flows, namely energy and greenhouse gas, using a life cycle inventory database. In this study, both steps are carried out using EPiC Grasshopper [58], a tailor-made plugin for quantifying embodied environmental flows in the Grasshopper Environment. EPiC Grasshopper uses the EPiC Database [69,70], which is currently the only database of embodied environmental flows coefficients for construction materials that uses the advanced hybrid life cycle inventory analysis approach, globally. This hybrid approach completes process based material data sourced from Ecoinvent [71] with top-down data. The motivation behind the selection of EPiC Grasshopper for this study lies in the solution brought to the significant truncation error associated with process data [70,72–74] and in the demonstrated robustness of the hybrid methodology of EPiC, which was validated in several studies for the Australian context [70]..

Three types of assemblies were defined: floors, façade and partition walls. Only the insulation material was varied in this study. The thickness of each material was calculated to maintain a U-Value of 0.24 W/(m^2·K), as prescribed by the EPB regulation for new constructions [75]. The useful physical characteristics of each material were sourced from TOTEM and EPiC. TOTEM is a Belgian tool for the calculation of the whole life cycle environmental impact of buildings [76].Table 2 presents the composition of each assembly and the associated embodied environmental flows per functional unit for stages A1–3. The wastage coefficient used for the calculation of the impacts of stage A5 and the service life of the materials used for the calculation of the impact of stage B4 are sourced from the EPiC database.

The operational energy demand is calculated using EnergyPlus [56], effectively including the life cycle stage B6. This engine was selected for both its ease of access from Grasshopper using Honeybee and its reliability (satisfies BESTest [77]). Furthermore, it has been used extensively in many scientific publications [32,38–40,42]. The simulations are performed with the geometries generated in Grasshopper via Honeybee, part of the Ladybug plugin suite for Grasshopper that establishes a bridge to EnergyPlus. Delivered energy is used to monitor the heating and cooling energy demands to facilitate the comparison between heating and cooling energy demands. For the cooling system a coefficient of performance (COP) of 4 is used to model a high-end system. For the heating system, a COP of 0.9 is used. The conversion to GHG emissions is performed by multiplying the final energy demand by 2.5 to obtain the primary energy demand as prescribed by the Belgian EPB

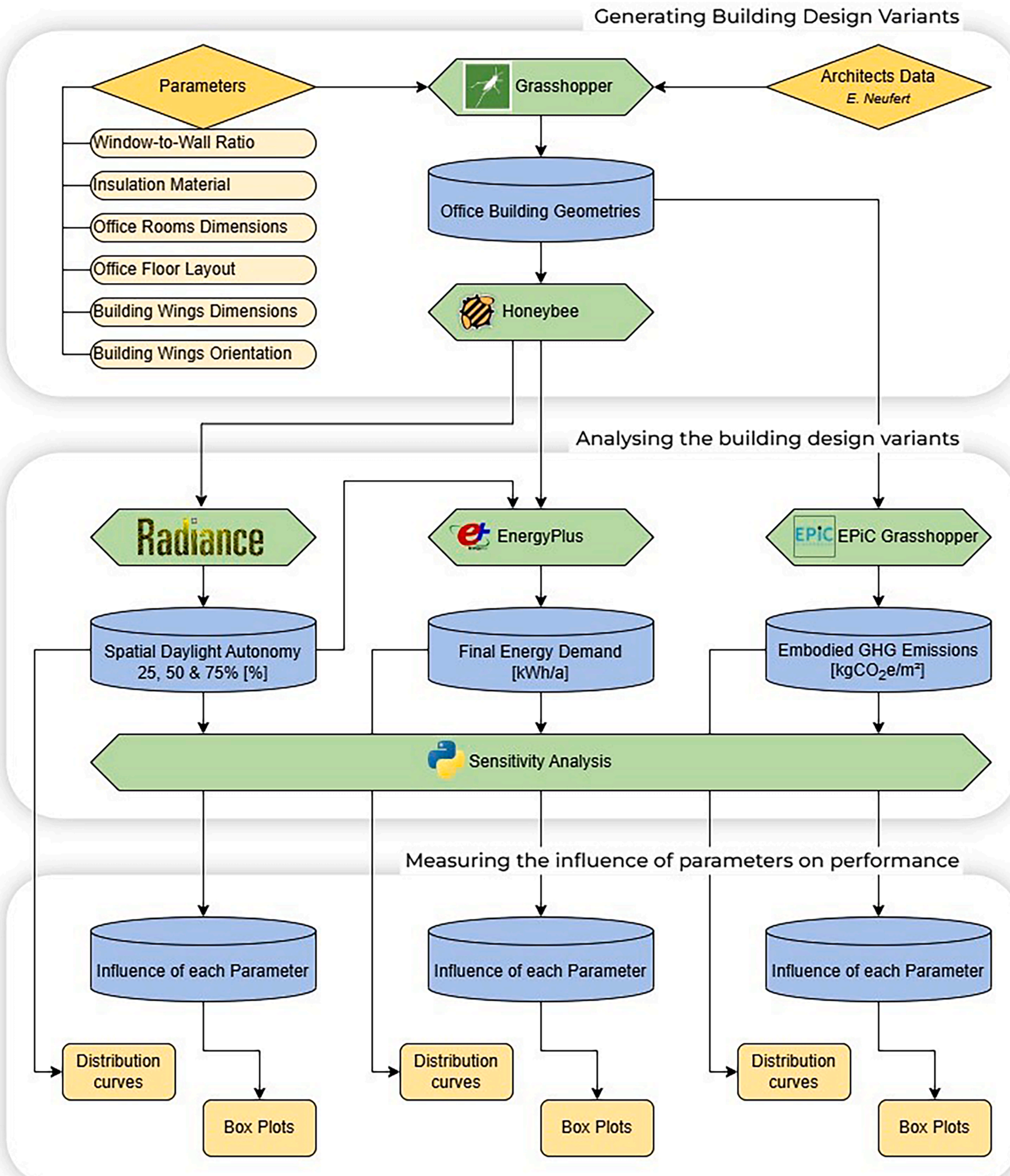

Fig. 2. Overall research design.

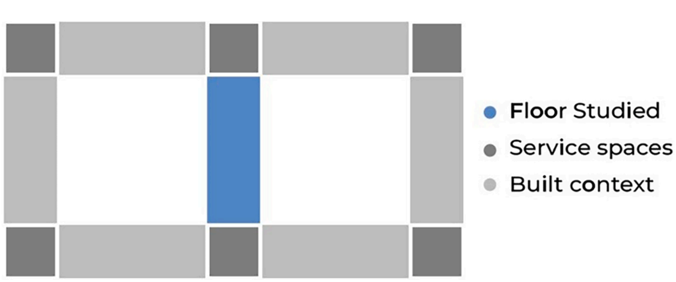

Fig. 3. Floorplan of the building modelled.

implementation [75]. Then the characterisation factor of the Belgian electricity mix listed in Ecoinvent 3.11 is applied [71].

The assessment of spatial daylight autonomy (SDA) starts by distributing a series of points in the assessed area, at a defined height. Then, the amount of light received by each point is measured using a time-step. The SDA is defined as the proportion of points that receive more than a certain amount of light for more than a certain time threshold. Daylight simulations are performed using Radiance [57], accessed in Grasshopper via Honeybee. The choice of Radiance is motivated by its ease of access in Grasshopper through Honeybee and by its extensive usage in research worldwide [78–80]. Honeybee provides an analysis component enabling to compute the SDA for given illuminance and time thresholds. The minimum illuminance was set at 300 lx

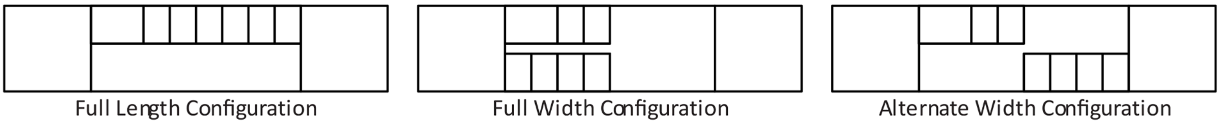

Fig. 4. Adopted distributions of office rooms in building wings used in the model.

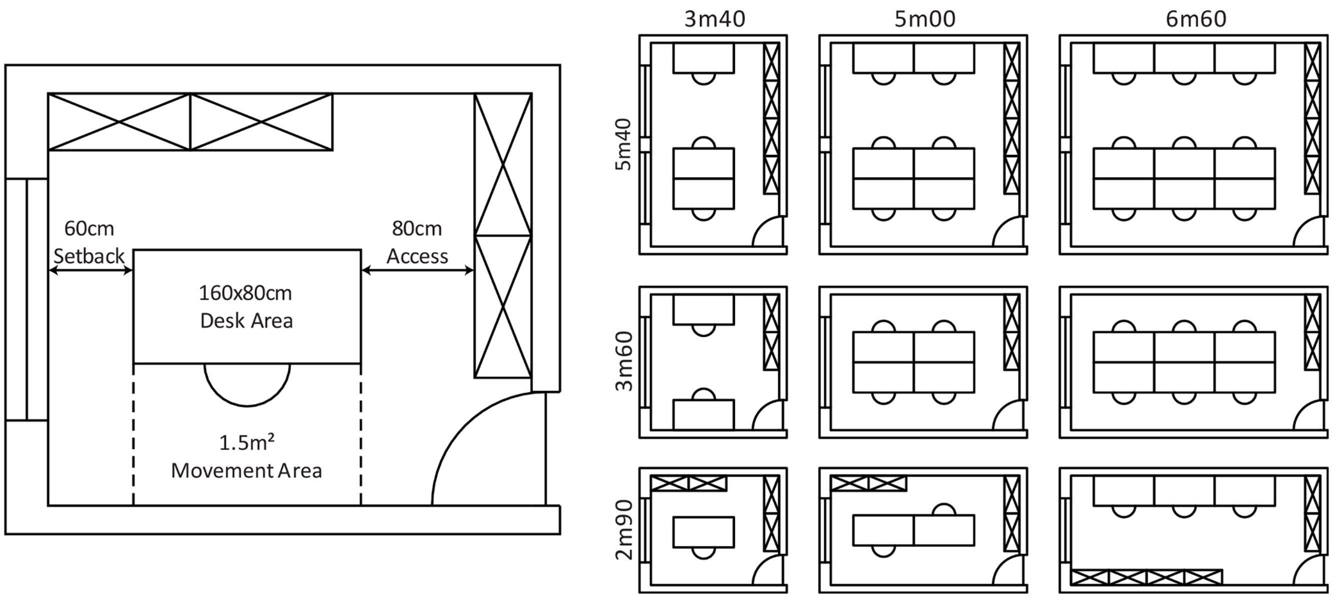

Fig. 5. Adopted office room sizes used in the model.

as recommended for office work. The analysis period was set from 8:00 to 17:00 every weekday. Three time thresholds were then defined: 25 % of the time, 50 % of the time and 75 % of the time.

The values used for the parameters accessible via Honeybee are reported in Tables A.2 and A.3 in Appendix A.

3.3. Measuring the influence of parameters on performance

A sensitivity analysis, derived from the Morris method [81], is conducted to measure the influence of a given parameter (e.g. insulation type) on modelling results (e.g. embodied energy) of an assessed system (e.g. office building, as defined above). The method relies on two steps. First, the differences in results are calculated for every pair of neighbouring scenarios, which differ by only one varied parameter. Then, the relative variations induced are plotted into a box plot.

A Python script was developed for this study to automate this step and directly provide the final statistics. The script operates in two steps: (1) sorting the results using pandas dataframes; and (2) compute the average difference in results for identical contexts. The following diagram describes the structure of the results data and provides an overview of the whole process.(Fig. 7).

4. Results

This section provides a comprehensive overview of the analyses conducted on the office floors generated via the method described in Section 3.1. A total of 972 variants were generated, with 324 used for thermal energy simulations, 243 for embodied energy and greenhouse

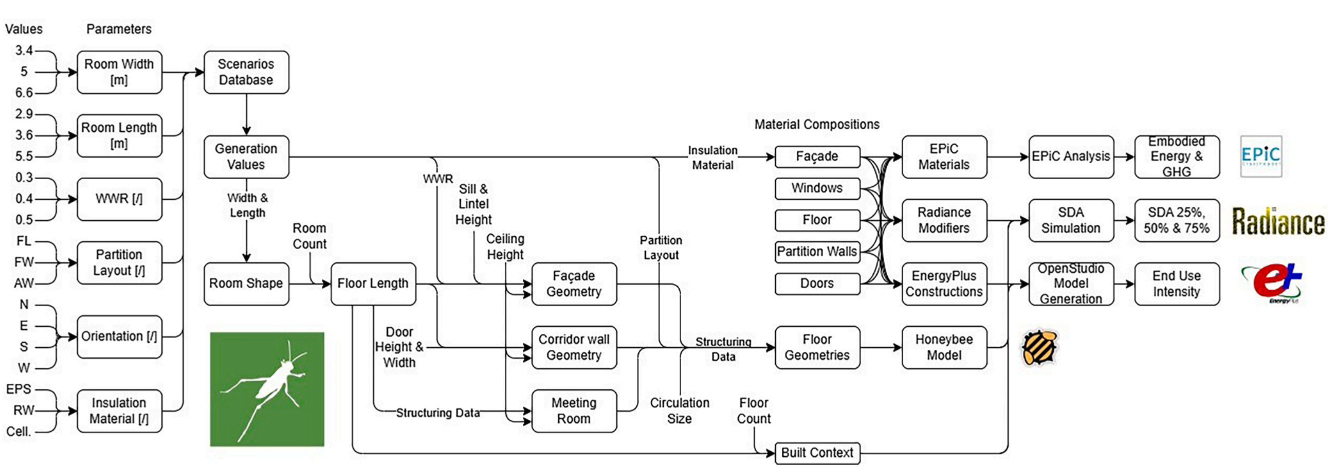

Fig. 6. Grasshopper algorithm used for the generation and analysis of the models.

gas emissions calculations, and 324 for SDA assessments. The results are structured into three subsections. First, the distribution of results across all three performance metrics — SDA, thermal energy demand, and embodied environmental flows — is presented using histograms and scatter plots, highlighting the diversity of variants achieved. Second, the most efficient clusters found in the first sub-section are deconstructed to find which values of each parameter induced these clusters. Third, a series of box plots illustrate the sensitivity of each metric to the generative parameters, effectively quantifying their influence.

To ensure the robustness of the conclusions, results for life cycle GHG emissions are presented using two normalisation units: per square meter and per capita. This accounts for the varying occupancy densities and areas across scenarios. Using both units allows comparison from both spatial and individual perspectives, providing confidence that trends observed are not an artifact of the chosen normalisation.

4.1. Results distribution

Fig. 8 presents the distributions of Spatial Daylight Autonomy (SDA), operational GHG emissions, and embodied GHG emissions across the analysed building variants. Each diagram illustrates the frequency of the results.

The SDA distribution includes three SDA thresholds: 25 %, 50 %, and 75 %. Each bar represents the number of variants that achieved that SDA value. For example, the peak of the orange graph indicates that around 12 scenarios achieve a SDA 75 % of 25 %. This means that 75 % of the area receives more than 300 lx for 25 % of the office hours. The distributions span over more than 50 % for all three SDA thresholds, highlighting the range of daylighting conditions across the dataset. SDA 75 % and SDA 25 % define the lower and upper boundaries of space illumination, respectively, while SDA 50 % exhibits a more uniform distribution. This makes SDA 50 % the preferred metric for sensitivity analysis, as it ensures clearer distinctions between parameter influences.

The two following graphs include the distributions of the embodied, operational, and whole life cycle (WLC) GHG emissions weighted by the floor area and the number of occupants, respectively. The shape of the distributions shows that the whole life cycle and operational GHG emissions are similar, while the embodied GHG emissions distribution appears narrower. The proximity of the operational and WLC distributions suggests that the WLC GHG emissions are mainly driven by the operational emissions.

Fig. 9 presents the ranges of contribution of the components of embodied, operational, and WLC GHG emissions. The WLC graph confirms the outstanding contribution of the operational emissions to the WLC of the building. It further reveals that this contribution is mainly due to the energy required for heating, followed by the embodied GHG emissions of the floor materials.

Table 2
Adopted material composition for the main assemblies of office buildings in the model and associated environmental flow per useful area.

Constructive element	Composition	Initial Embodied Energy [MJ/m²]	Initial Embodied GHG emissions [kgCO2e/m²]
Partition Wall	Timber Frame Structure Plasterboard on both side Water-based paint	637.97	39.04
Façade - EPS	8 mm Fibre cement weatherboard 130 mm Expanded Polystyrene 390×190×190 mm Concrete blocks 0.2 mm low-density polyethylene 13 mm Plasterboard Water-based paint	1428.24	104.27
Façade - rockwool	8 mm Fibre cement weatherboard 140 mm rockwool 390×190×190 mm concrete blocks 13 mm plasterboard Water-based paint	1545.26	119.62
Façade – cellulose	8 mm Fibre cement weatherboard 190 mm cellulose 75×180 mm softwood frame 390×190×190 mm concrete blocks 13 mm plasterboard Water-based paint	1056.17	86.91
Slab	Carpet 200 mm reinforced concrete Water-based paint	1828.61	174.21
Door	90×35 mm Softwood frame 90×70×1000 mm Softwood lintel 2 × 18mmx2.05mx0.82 m MDF board	824.05	45.03
Window	Double-glazed window Aluminium Frame	2200.07	169.64

4.2. Cluster analysis

Fig. 10 plots SDA 50 % against WLC GHG emissions weighted by floor area and number of occupants. The first graph presents a neat pareto front, suggesting a trade-off between environmental performance and visual comfort. The second graph does not present a clear pareto front but rather displays clear horizontal clusters, which limits the number of optimal solutions. The highlighted data points were isolated and the count of each value of every parameter was calculated. The results of this deconstruction of these regions is presented in Fig. 11.

Fig. 11 shows that the clusters selected contained data points generated mainly with the maximal room length included in the scope, but a median to low room width. A slight discrepancy can be observed between the per surface and per capita ponderations. In the per capita graph, the cluster is dominated by the highest WWR while in the per surface graph it coexists with the median WWR. Density parameters were introduced to capture both the geometric compactness of the floor layout and the available space per user as an indicator of spatial comfort. These parameters were derived from the initial parameters used for the generation of the scenarios. For instance, geometric density is defined as the ratio of the width of the floor to its length, expressing the compactness of the plan configuration. A higher geometric density means a more compact floor. Its value ranges here from 0.205 to 0.655, the pareto front is here characterised by a rather low geometric density. Occupancy density, in contrast, serves as the spatial comfort indicator and is defined as the number of occupants per square meter. A higher occupancy density means less comfort for each occupant. For the 792 variants, occupancy density ranges from 0.078 to 0.219, this pareto front is therefore characterised by a high occupancy density.

4.3. Sensitivity of the results to the parameters

Fig. 12 presents the results of the sensitivity analysis of key design parameters on SDA 50 % and WLC GHG emissions weighted by area and per capita Each box plot represents the statistical distribution of variations observed when modifying the value of a single parameter at a time.

For SDA 50 %, room width emerges as the most influential parameter, followed closely by WWR, length and occupancy density. For example, increasing room width results in a decrease in SDA 50 % of up to 42 %, with an average reduction of around 22 %. This is expected, as deeper rooms require more daylight to maintain adequate illumination.

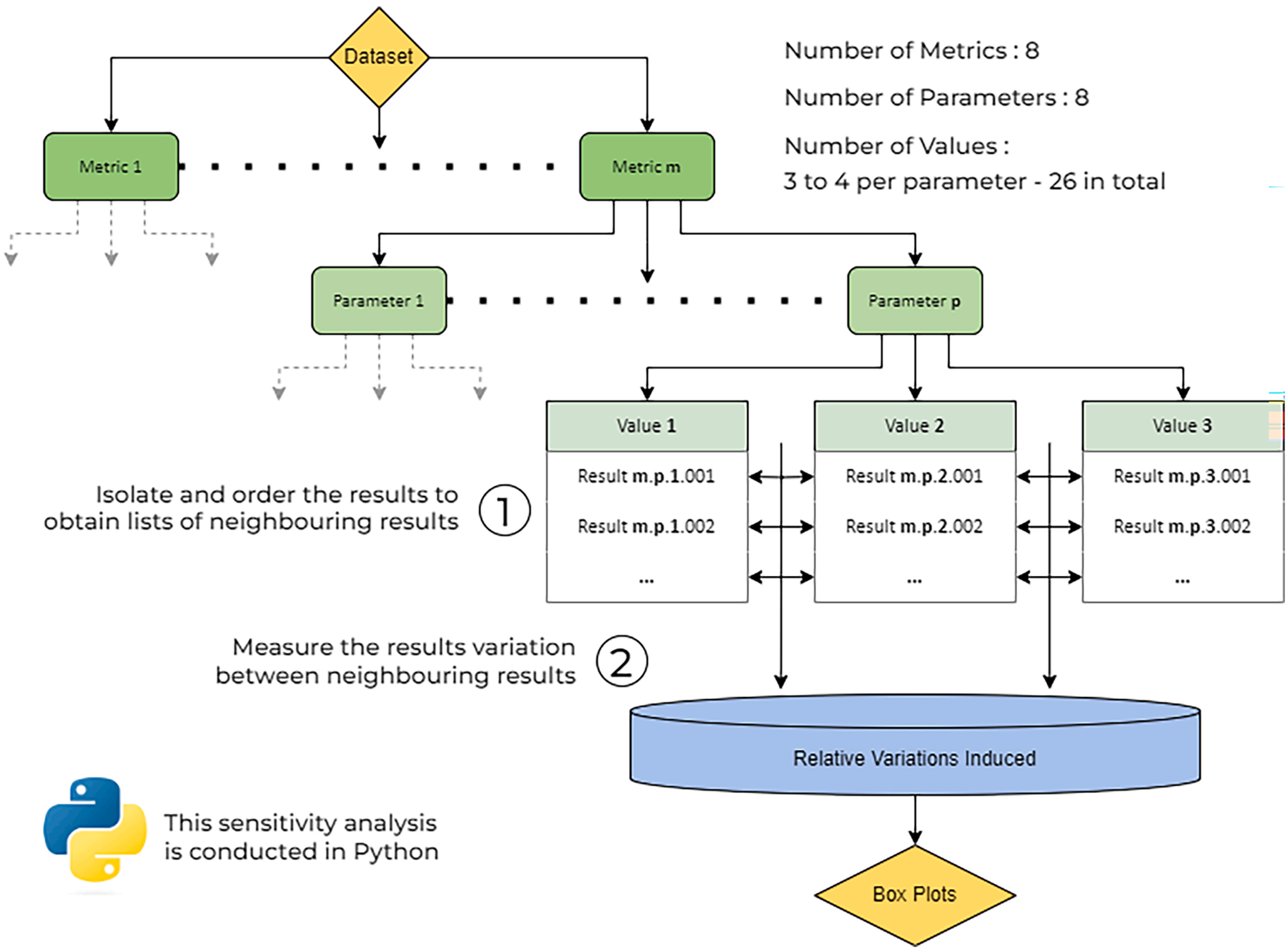

Fig. 7. Adopted data structure for the results of the sensitivity analysis of the model.

Similarly, a 10 % increase in WWR leads to a variation of SDA 50 % of up to 30 % with an average of 18 %. The remaining design parameters all appear to have a small but perceptible influence on the results. The partition layout in particular induces an increase in SDA 50 % of up to 20 %.

For LC GHG emissions, the conclusions are not modified by the ponderation chosen, but weighting the results by the surface does decrease the relative influence of the parameters compared to the occupancy ponderation. The width and the length of the rooms still appear as the most influential parameters, increasing their value do lead to a decrease in WLC GHG emissions. The absolute difference in parameter influence when changing the normalisation factor is provided in Table A.1 in Appendix A.

5. Discussion

The results presented in Section 4 and synthetised in Table 3 display the outstanding influence of room width and occupancy density on both the visual comfort and life cycle GHG emissions of the model. Wider wings limit daylight penetration and increase energy demand for lighting and HVAC, thereby impacting both comfort and environmental performance. Similarly, the window-to-wall ratio (WWR) influences solar gains and daylight availability – affecting spatial daylight autonomy (SDA) more than GHG emissions – which confirms its relevance in the design process. These observations highlight the trade-off between occupant comfort and environmental impact. The layout of partition walls also emerges as a critical parameter, enabling improvements in visual comfort without significantly altering GHG emissions. However, acoustic comfort was not assessed in this study and may influence these conclusions. Finally, using two different functional units (occupancy and area) allowed for a more nuanced interpretation of the results, enhancing the robustness of the findings.

Interestingly, the influence of WWR on both SDA and life cycle GHG emissions proved to be lower than initially expected, particularly when compared to the findings for a London office of Gauch et al. [38]. Nonetheless, this limited impact on SDA aligns with Goia et al. [67], who observed a saturation of daylight autonomy for WWR values starting around 0.4 under similar climatic conditions and across all orientations. In our study, WWR was varied within the optimal range (0.3–0.5) identified by Ma et al. [68]. Consequently, the variations between 0.3 and 0.4 produced noticeable effects, while the changes between 0.4 and 0.5 had a much smaller influence. It can thus be inferred that exploring lower WWR values would likely produce a marked but negative effect on SDA, without significantly altering the life cycle GHG results. Conversely, increasing the WWR beyond 0.5 would probably not yield substantial SDA improvements, while it would raise life cycle GHG emissions. Extending the value range in future studies would therefore be valuable to verify the trends identified by Ma et al. and to test the stability of these observations under more extreme design scenarios.

Geometric compactness of the building has been identified by Gauch et al. [38] as a decisive design parameter influencing life cycle GHG emissions. Their results indicate that compactness exerts a stronger

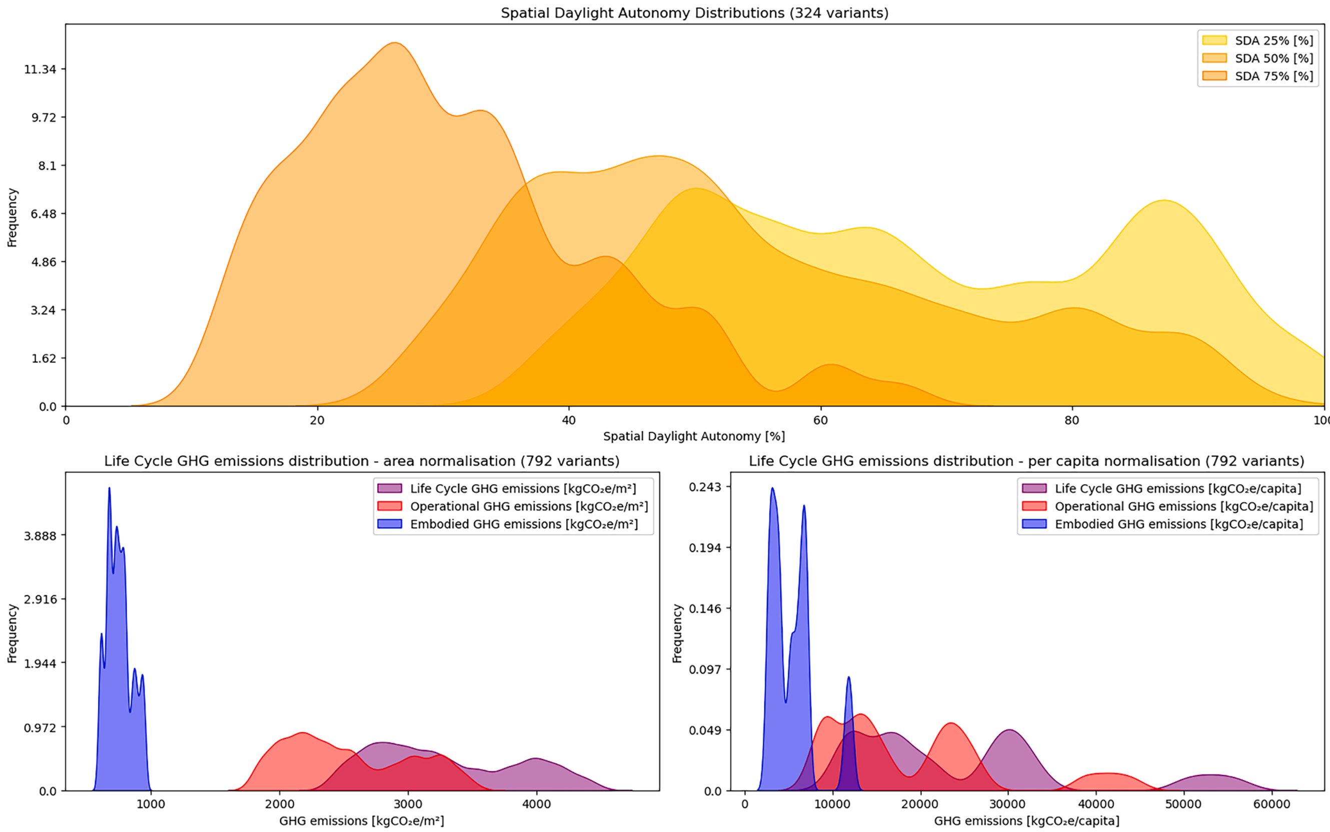

Fig. 8. Distribution of the results for SDA and GHG emissions metrics.

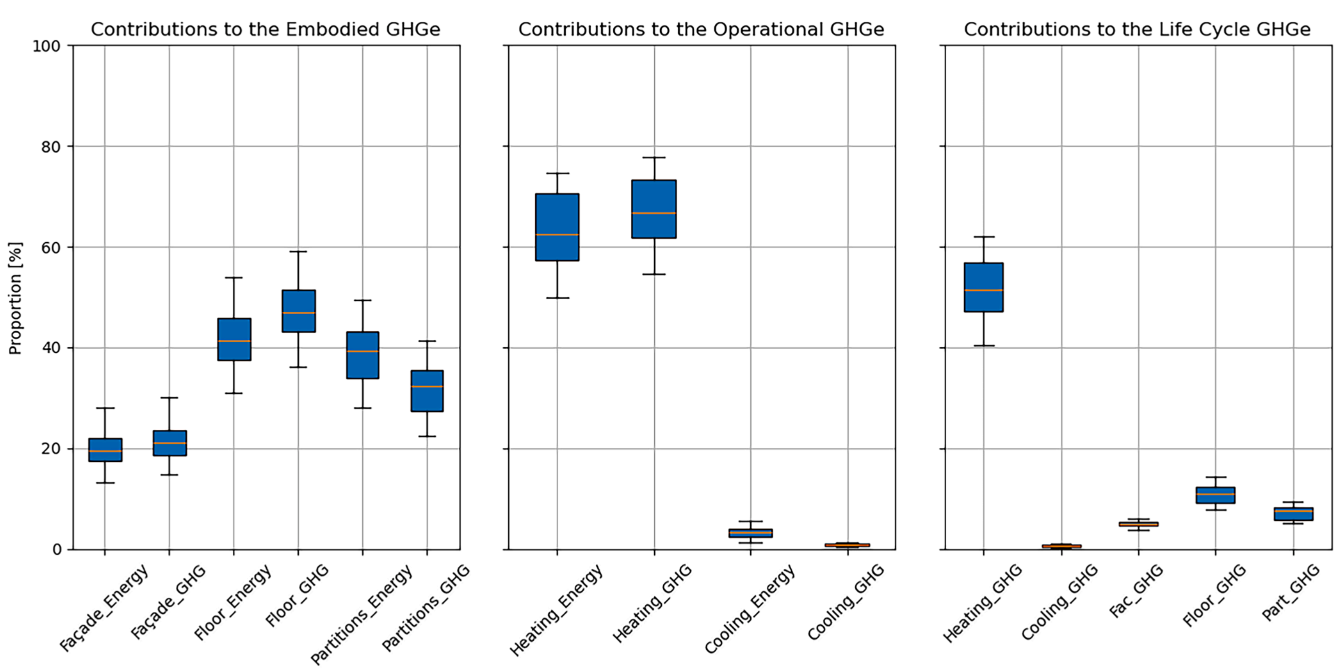

Fig. 9. Contributions of the components of the embodied GHG emissions and heating and cooling energy demand to the embodied, operational, and whole life cycle GHG emissions.

impact on emissions than WWR, which is consistent with the trends observed in the present study. The optimal design configurations identified by Gauch et al. combine a maximal compactness with minimal WWR. Both parameters bear a significant but inverse influence over SDA, which confirms the existence of the trade-off between environmental burden and lighting comfort. Our results reveal that SDA appears more sensitive to variations in compactness than life cycle GHG emissions, suggesting that geometric compactness is a decisive lever for balancing comfort and environmental impact. Future work should therefore focus on the exploration of this trade-off.

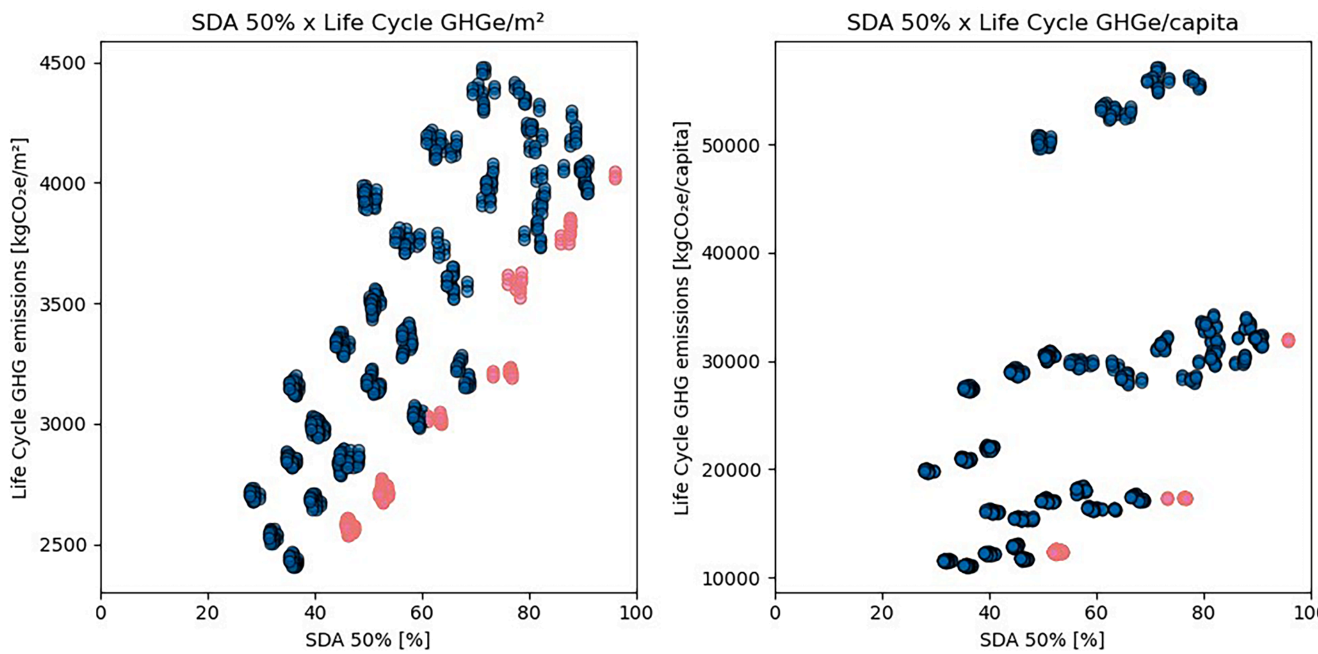

Fig. 10. Visualisation of the relation between life cycle GHG emissions and SDA 50 %.

5.1. Related works

We identified two studies with a similar method and aim. The study by Androsics-Zetz et al., 2022 [82] aims to algorithmically generate office floor plans and to conduct energy and comfort simulations afterward. Their approach uses square modules and an extensive set of rules to produce usable workspaces. They identified 17 possible floor configurations as compared to the 27 identified in this study. The algorithmic nature of their method enables a higher diversity of configurations and an easier implementation using object-oriented programming. However, it also results in uncommon shapes that are less realistic. The next step of their study is to perform simulations on the floorplans generated. The results of this step are not yet published.

The study of Gauch et al., 2023 [38] uses a similar approach to ours. They rely on a higher number of parameters than our study, i.e. 31 parameters compared to seven. The authors use the same categories of parameters as in this paper, but also model the structure of the building and vary the type of occupancy and the climate. They find that the shape of the building bears a significant influence on the system through the variation of the compactness and the floor area, which corroborates the findings of our study. Additionally, their detailed modelling of the structure reveals its significance influence on embodied flows, making it more influential than the façade, as identified by various studies, e.g. [83] and [84].

5.2. Significance

The novelty of this study lies in the integration of daylight autonomy evaluation and life cycle GHG emissions assessment within a unified parametric workflow. This approach enables the simultaneous analysis of embodied and operational impacts alongside daylight performance, allowing a consistent comparison of parameter influences on both environmental and lighting outcomes—a combination rarely addressed in existing research.

The use of variable parameters and associated values is significant for the early design process, because architects, engineers, and other building designers have not yet made many choices, and are not able to understand their significance in terms of the full life cycle environmental performance of the project. We defined reference values based on established reference books in the architectural design space, e.g. Neufert rulebooks [66] on operational energy efficiency in buildings [75], and our own empirical experience (e.g. window-to-wall ratio). In general, we expect that designers will consider other relevant parameters (e.g. renewable energy systems with associated design choices), that influence the design process by extending the scope of parameters and by anticipating favourable building designs. Furthermore, the dual consideration of energy and comfort presents a more comprehensive view of the performance of a building design. This ensures that the conclusions are more balanced and consider both environmental effects and occupant well-being.

Grasshopper is deemed a robust and accessible tool for the generation and analysis of the model variants for programming beginners. However, the way it handles random access memory (RAM) poses a significant limitation to the exploration of a large set of scenarios. Using the Anemone [85] plugin for Grasshopper to loop through a list of pre-generated scenarios identifiers proved to be an efficient solution to this problem. Python is however advised to replace Grasshopper for practitioners and researchers with programming skills to better streamline and control the workflow.

5.3. Limitations

The novelty of the approach presented in this study implies that it can be improved. This study helped identify several limitations that must be considered in future research.

The sensitivity analysis results highlighted the significant influence of certain parameters, while others appeared to have almost zero influence on the system. This variation of the influence of the parameters could be a result of a narrow ranges of values that each parameter can take. It is also possible that these parameters truly have a negligible influence on the selected metrics which is mainly due to their interaction with other parameters. In which case, employing a sensitivity analysis method that evaluates the potential interactions between parameters could highlight this. In this study, the spatial layout of the partition walls was proved to have a low but existing influence on the system, this parameter could be explored further to provide more robust guidelines to designers.

In addition, it would be interesting to explore the full range of

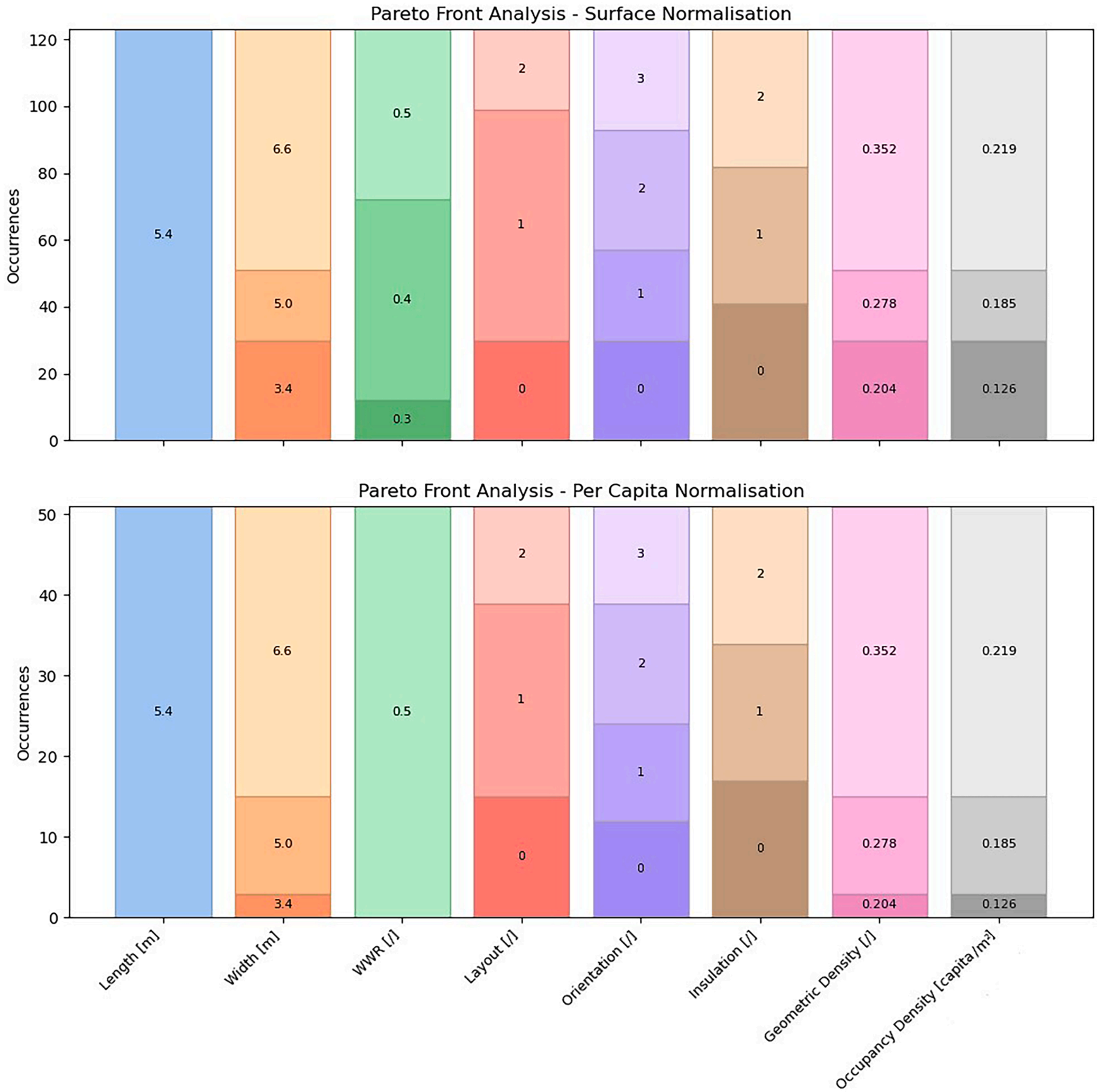

Fig. 11. Frequency of the values of each parameter for the best performing scenarios in terms of life cycle GHG emissions and SDA 50 %.

variation of the influential parameters. Knowing the limit of their influence should lead to more optimised and robust conclusions in terms of design guidance. Especially, the occupancy and geometric densities are found to be particularly influential parameters but were not explicitly included as initial parameters in this study Exploring more possible values to these parameters can help better assess their full potential.

Additionally, the life cycle inventory database used in this study was developed for the Australian context [70]. Redoing the calculations for the European context might change the relative contribution of the embodied GHG emissions and therefore the conclusions, notably because of differences in electricity mixes. Ecoinvent [71] could fulfil this purpose as it was used as the foundations for EPiC, although it lacks the input-output completion data used in EPiC. The choice of EPiC was indeed motivated by the robustness of its underlying hybrid methodology rather than by geographic specificity.

Finally, the simulations carried out in this study used Brussels climate and Belgian references, notably the Walloon U-value target of 0.24 W/m².K. Brussels climate is categorised as maritime by the European Environmental Agency [86]. This climate covers all Western Europe, which facilitates the comparability to other studies in the same area. However, reproducing this experiment in other regions will result in different results and conclusions due to differences in climate, and construction practices and standards. Thermal comfort aspects, including occupant satisfaction thresholds defined in standards such as

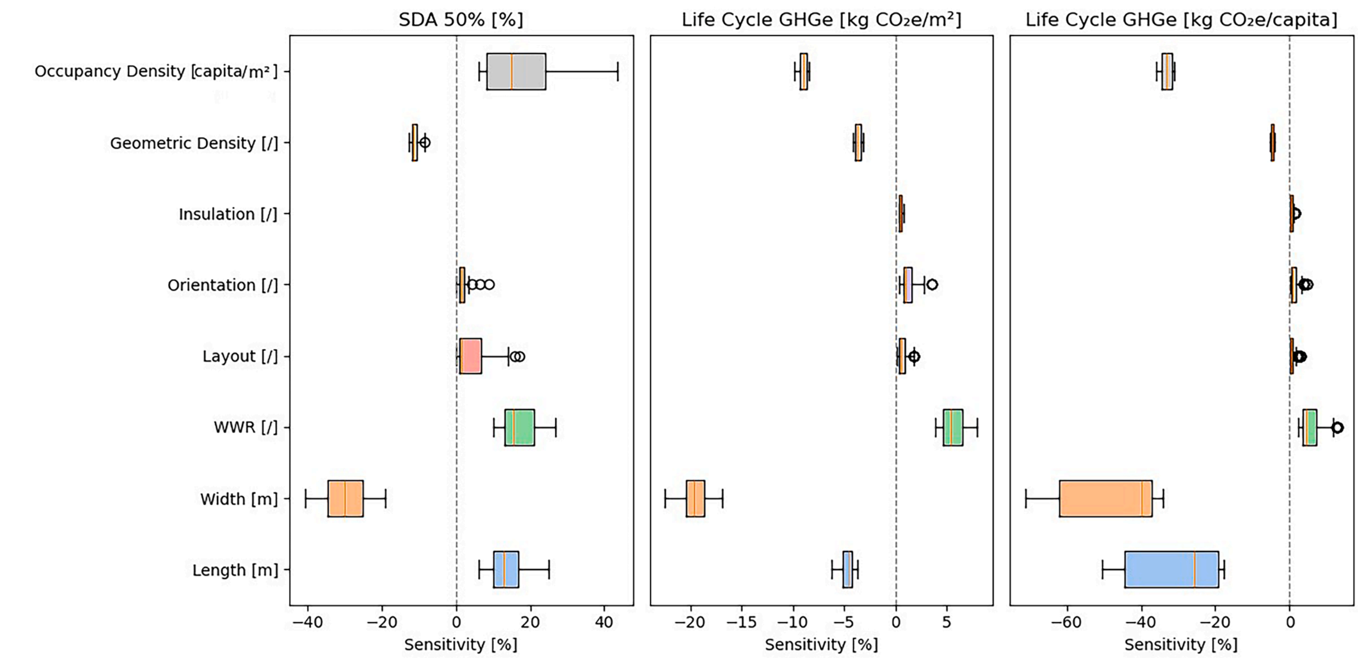

Fig. 12. Relative variation induced by changing the parameters values.

Table 3
Summary of the influence of key geometrical parameters of the embodied energy and greenhouse gas emissions, thermal energy demand and daylight autonomy of office buildings.

Parameters	Spatial Daylight Autonomy	Life Cycle GHG emissions
Room Width	Highest influence	Highest influence
Room Length	Median influence	High influence if weighted per capita
Window-to-Wall Ratio	Median influence	Low influence
Spatial Distribution	Clear but limited influence	Low influence
Orientation	Low influence	Low influence
Insulation Material	N/A	Neglectable influence
Geometric Density	Median influence	Low influence
Occupancy Density	High influence	High influence

ASHRAE 55 and EN 16,798, were not considered and remain outside the scope of this study but constitute a valuable direction for future research. The inclusion of cost and social impact would also complete the scope of future studies and enable the derivation of conclusions with unprecedented robustness.

6. Conclusion

Human activities are altering our environment and the construction sector is a critical contributor to this change. Both research and practice need to speed up the ecological transition process to tackle this issue, but without leaving comfort considerations behind. The contribution of this study resides in the elaboration of an integrated parametric workflow for evaluating GHG emissions and daylight autonomy during the early-design stage of office buildings and comparing the influence of design parameters on these aspects. This approach enabled the generation of 972 theoretical office floors based on design parameters. This set of parameters covers the shape and the envelope of the building as well as the layout of the floors. The implementation of the method developed was realised using Grasshopper and Python. Each scenario generated was then analysed through the lens of two main metrics: life cycle greenhouse gas emissions and spatial daylight autonomy. Finally, a broad sensitivity analysis revealed the influence range of every parameter involved. The results of this study highlighted the significance of the compactness of a building and the trade-off between the comfort of the occupants and the environmental impact of the building. Compactness and internal layout were found to have a greater influence on spatial daylight autonomy than on life cycle GHG emissions. Therefore, these parameters appear as critical to reach optimal design solutions and constitute great focus points for future research.

Such parametric workflow could serve as exploration tools for various stakeholders in project development, including designers, architects, engineers, urban planners and investors. It could support creating large databases of project scenarios that would inform the dynamic and often unpredictable design process quickly and efficiently, leading to better performing building projects. Future studies can benefit from the expandable Grasshopper definition and Python code developed for this study, to expand the scope of the analyses.

Tables A.2,A.3

CRediT authorship contribution statement

Maxime Dasse: Writing – original draft, Visualization, Software, Methodology, Formal analysis. **Katarina Slavkovic:** Writing – review & editing, Supervision, Conceptualization. **André Stephan:** Writing – review & editing, Supervision, Conceptualization. **Emilie Gobbo:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

The files used for generating the variants and analysing the data are available in a GitHub repository [87]

Table A.1
Absolute difference in parameter influence between per square meter and per capita normalisation.

	Room Length	Room Width	WWR	Layout	Orientation	Insulation	Geometric Density	Occupancy Density
Average	25.51	27.7	0.04	0.0	0.02	0.0	1.03	24.11
10th percentile	42.25	46.33	1.6	0.1	0.08	0.09	1.09	25.46
25th percentile	39.38	41.57	1.06	0.1	0.21	0.11	1.06	25.2
50th percentile	21.06	20.3	1.1	0.02	0.17	0.08	1.03	24.13
75th percentile	15.06	18.57	0.57	0.01	0.14	0.13	0.98	22.93
90th percentile	13.85	17.69	3.4	0.08	0.3	0.17	0.97	22.75

Table A.2
Manually set parameters for the operational energy demand simulations.

Parameters	Values
North	Determined by the orientation parameter
Climate	BEL_Brussels.064510_IWEC
Start day of the week	Monday
Timestep	1/hour
Terrain	Suburbs
Building Type	Medium Office
Occupancy schedule	Monday to Friday, 8:00–18:00
Fraction of lightbulbs that are dimmable when the room receives enough daylight	0.5
Minimum power for dimmable lightbulbs	0.6
Dimmable lightbulbs can be switched off when at minimum power	True
Cooling setpoint	25 °C
Heating setpoint	19 °C
Cutout difference with setpoints	1 °C
Ventilation system type	DOAS with fan coil chiller with boiler
Ventilation system vintage	2019
Demand control ventilation	True
Minimum indoor temperature for opening windows	22 °C
Maximum indoor temperature for opening windows	24 °C
Minimum outdoor temperature for opening windows	16 °C
Maximum outdoor temperature for opening windows	24 °C
Minimum temperature difference for opening windows	4 °C
Discharge coefficient for natural ventilation	0.65
Windows cross ventilation	True
Air tightness	0.0003 m^3/s
Sizing method	Ideal air system

Table A.3
Manually set parameters for the spatial daylight autonomy simulations.

Parameters	Values
Grid size	0.5m
Grid position	1 m above ground
North	Determined by the Orientation parameter
Climate	BEL_Brussels.064510_IWEC
Occupancy Schedule	Monday to Friday, 8:00–18:00

Data availability

I have cited a repository in which the code is made available.

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