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Key drivers of life-cycle environmental and cost assessment of windows for different European climate zones

Shiva Saadatian [a,b,*], Carla Rodrigues [a], Fausto Freire [a], Nuno Simões [c,d]

[a] University of Coimbra, ADAI, Department of Mechanical Engineering, Pólo II, Rua Luís Reis Santos, 3030-788, Coimbra, Portugal
[b] University of Coimbra, Institute of Interdisciplinary Research, Casa Costa Alemão, Pólo II, Rua Dom Francisco de Lemos, 3030-789, Coimbra, Portugal
[c] Itecons - Institute for Research and Technological Development in Construction, Energy, Environment and Sustainability, Rua Pedro Hispano, 3030-289, Coimbra, Portugal
[d] University of Coimbra, ADAI, Department of Civil Engineering, Pólo II, Rua Luís Reis Santos, 3030-788, Coimbra, Portugal

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ABSTRACT

Windows are challenging building components regarding their life-cycle performance, which are influenced by parameters that often present trade-offs between environmental impacts and costs. To support the selection of windows with the lowest environmental and cost impacts in an early-design stage of buildings, it is essential to identify the key drivers to reduce the time and effort of a life-cycle assessment (LCA). A sensitivity analysis was performed to identify and rank the parameters that contribute the most to the variability in life-cycle global warming and cost of windows for three European climates. A set of alternative window configurations combining window- and operation-related parameters was investigated. The results showed that window-related parameters are more influential than operation-related parameters. The highest influential parameter on global warming and cost was window-to-wall ratio, for all orientations and locations. Other influential parameters depend on the location: for warmer climates, smaller windows are recommended or bigger windows with low solar factors; for colder climates, bigger windows are recommended or small windows with high solar factors. Thermal transmittance value has a large influence on smaller windows in warmer climates and on bigger windows in colder climates. The identification of key influential parameters and their ranking is important to support the environmental and cost LCA at an early-design stage of buildings, when window selection is flexible and more informed decisions can be made to promote lower impacts and costs.

1. Introduction

Windows are one of the most challenging building components as they are complex systems with various elements, materials, quantities and very specific properties. Furthermore, windows play a crucial role not only in affecting daylight and view [1,2], but also in the overall energy needs of buildings [1,3,4], and, consequently, in the environmental and costs during a building life-cycle. Additionally, as buildings move forward to nearly-zero energy targets, they can promote climate change mitigation and adaptation in line with the Paris Agreement goals, particularly, to limit global warming below 2 °C (preferably 1.5 °C) by reducing greenhouse gas

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[*] Corresponding author. University of Coimbra, ADAI, Department of Mechanical Engineering, Pólo II, Rua Luís Reis Santos, 3030-788, Coimbra, Portugal.
E-mail address: shivasaadatian@student.dem.uc.pt (S. Saadatian).

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emissions to pre-industrial levels [5]. So, it is essential to identify the key drivers of global warming and cost of windows to reduce the time and effort needed to perform a life-cycle assessment (LCA) of such complex systems, and be able to effectively support the selection of windows with the best environmental and cost performance in an early design stage of buildings.

Additionally, there are challenges in the building design when selecting a window, for instance, defining the best window size, to promote natural light as well as low heating and cooling needs. These challenges can be more complex when combining environmental and cost life-cycle assessment of windows, realizing that, to promote low-cost and environmentally friendly windows, numerous parameters need to be defined, with a contradictory nature between themselves [6–8]. Trade-offs can be identified in the definition of window-related parameters (i.e., thermal transmittance value, solar factor, window-to-wall ratio, orientation) and operation-related parameters (i.e., number of occupants and ventilation rate), meaning that an increase in a parameter value can lead to a decrease in environmental impacts but an increase in costs. In particular, it is difficult to identify at early design stage of buildings which parameters are the most relevant to improve the life-cycle environmental and economic performance of windows. Sensitivity analysis is an important tool to identify the most influential design variables in buildings' performance [9,10].

Numerous studies have assessed different window-related parameters to improve the energy efficiency of buildings, overlooking the ranking of influential parameters on the environmental and cost performance of buildings in a life-cycle perspective [7,11–16]. For example, Tavares et al. [17] performed a sensitivity analysis to compare the energy needs for space heating and cooling of several window solutions and orientations with different transition ranges for the optical properties through incident solar radiation, without presenting the most influential parameters. Singh et al. [18] performed a sensitivity analysis on energy and visual performances for an office building with external venetian blind shading in a hot-dry climate. The results compared the energy and visual performances of window solutions differing in window-to-wall ratio (WWR), glazing type, the blind orientation, and the slat angle. Dussault & Gosselin [19] performed a sensitivity analysis to assess the relative effect of the main building design parameters on energy and comfort improvements related with the use of a smart window. Scorpio et al. [15] performed a sensitivity analysis to analyze the benefits of using dynamic electrical-driven glazing to refurbish windows of historical buildings only during the operation phase from an energy, environmental and visual points of view. Recently, Heydari et al. [20] assessed the influence of changing the gap between the glass panes and thickness on the cooling and heating loads of the building in Iran. None of above-mentioned studies have studied the influence of window-related parameters together with the operational parameters such as occupancy level and ventilation rate on the cost and environmental life-cycle of windows.

Several sensitivity analysis metrics have been applied to compare the performance of different design solutions, regardless of investigating the ranking of influential parameters on the results [21]. For example, Tian and De Wilde [22] implemented two sensitivity analysis metrics, Standardized Regression Coefficients (SRC) and Adaptive Component Selection and Smoothing Operator (ACOSSO), to evaluate the thermal performance of a campus building in the UK. The results showed that the influential variables on annual carbon emissions were lighting gains, solar heat gain coefficients of windows, and cooling degree days, in charge of around 95% of the output variances. Ballarini and Corrado [23] used Standardized Regression Coefficients (SRC) for sensitivity analysis on the cooling energy needs of alternative window solutions for an Italian residential building. The results showed that the most affecting parameters were window area, window insulation, and solar shading. Hyun et al. [24] used Morris method for sensitivity analysis on the performance of natural ventilation in a Korean residential building. The results showed that the influential factors were wind velocity and window opening area. Singh et al. [18] has applied the extended FAST method for sensitivity analysis of glazed component variables on energy and daylighting performances of an office building. The extended FAST method calculates the first order sensitivity index and total order sensitivity index in order to investigate the contribution of each variable to the total variance using the same sample set.

Window-related parameters have been commonly studied in the literature to compare LCA results of different window solutions; however, without assessing the operation-related parameters (ex. number of occupants, ventilation rate) and detailing the influence of combining both window- and operation-related parameters to improve the life-cycle environmental and economic sustainability of windows for the buildings. For example, standard sized windows (1.82 m^2) with alternative framing and glazing solutions (differing in thermal transmittance and solar factor) were assessed firstly in terms of embodied impacts by Saadatian et al. [25], and secondly in terms of life-cycle cost and environmental impacts by Saadatian et al. [26], regardless of assessing the sensitivity of the results to the input parameters as well as considering other influential parameters (i.e. WWR, and operation-related parameters). There are studies which have performed sensitivity analysis on the LCA of window solutions during the operation phase [27,28], but disregarding the environmental performance of windows over their entire life cycle. An exception is the work of Salazar [29] that assessed the influence of the service life of the windows, as well as installation and resource location, on the total life-cycle impacts of windows.

There is still a lack of trade-off analysis between window- and operation-related parameters influencing the environmental and cost performance of windows. Among window-related parameters, the majority of studies have been focused on WWR to investigate the potential energy savings regarding heating, cooling, and lighting in buildings, while the other parameters have been overlooked in a trade-off analysis [30–34]. For example, Lee et al. [32] assessed various window configurations to optimize the annual heating, cooling and lighting needs in different Asian climates. The results showed that WWR was the most influential variable on operational energy demands of the building. Meanwhile, these studies suggested the optimal WWR fixed at 25%, except for the north orientation in the warmest locations. On the other hand, Su and Zhang [28] have measured the environmental impacts of operational performance of various windows with WWR ranges of 10–70% in different orientations, for a typical Chinese office building. Marino et al. [35] investigated the influence of window size and a switchable shading on the energy consumption of an Italian office building.

Research on the influence of the orientation and climate data for windows has been mostly focused on the energy performance of windows, and rarely assessed the integrated economic and environmental performances. However, none of the reviewed literature investigated the ranking of both window- and operation-related parameters based on the influence on the economic and environmental

LCA of windows. In addition, the influence of occupancy level and the flow rate of outside air into a building (ventilation rate) have not been investigated in the environmental and cost life-cycle assessment of windows, although these parameters can highly affect the operational cost and environmental impacts of windows. To promote LCA as a decision support tool with more robust results, sensitivity analyses are crucial to identify the key parameters that influence the environmental and economic performances [36].

The novelty of this article is to investigate the key parameters influencing the life-cycle global warming and cost of windows, as well as ranking them via sensitivity analysis, to easily prioritize the most important parameters to be defined when selecting windows in an early-design stage of buildings. The existing LCA studies of window solutions have not addressed a range of operation-related and window-related parameters to identify which parameters are the most relevant to improve the life-cycle environmental and cost performance of buildings, depending on the location. Operation-related parameters, such as number of occupants and ventilation rate, are typically fixed variables in LCA studies of windows.

The main goal of this article is to perform a sensitivity analysis to identify the key drivers and rank the parameters that contribute the most to the variability in life-cycle global warming and cost of windows, considering various climate regions in Europe. Sensitivity analysis can be a useful tool to realize the relationship between model inputs and outputs and quantify the difference between life-cycle global warming and cost of different window configurations. A large number of window solutions were comprehensively assessed combining several window-related parameters (i.e. thermal transmittance value, solar factor, window-to-wall ratio, orientation), as well as investigating the influence of operation-related parameters (i.e. number of occupants and ventilation rate) on the life-cycle global warming and cost of windows.

2. Materials and methods

An environmental, energy and cost life-cycle assessment has been applied to estimate the cost and global warming impacts of different window solutions combining several window-related parameters (i.e. thermal transmittance value, solar factor, window-to-wall ratio, orientation), as well as assessing the operation-related parameters (i.e. number of occupants and ventilation rate), for a reference office room located in three European climate regions. Operational energy was calculated using thermal dynamic simulation, previously validated with respect to EN 15265 (2007) [37]. This European Standard defines assumptions, boundary conditions, as well as a procedure to validate dynamic calculation methods for the calculation of the annual energy needed to heat and cool spaces in a building or a part of it. This analysis expands on previous LCA work described in Saadatian et al. [26], which performed a comprehensive LCA on a limited number of window alternatives with the same area. The present article expands on the dataset (number of alternatives) and advances on performing a sensitivity analysis to identify the parameters driving global warming and cost of windows. A larger number of window solutions have been comprehensively assessed combining several window- and operation-related parameters, as detailed in Table 1. Based on those results, a sensitivity analysis has been performed to identify and rank window-related parameters based on their influence to the variability in the cost and global warming LCA results of windows depending on climate and window orientation.

2.1. Scope, life-cycle model and window-related parameters' definition

A life-cycle model and inventory was developed and implemented for alternative window solutions applied to a reference room (5.50 m × 3.60 m × 2.80 m) [38], located in three European climate regions: Portugal, Germany and Cyprus. For each climate region a specific location for the reference room was selected based on their climate characteristics (Heating Degree Days - HDD): Coimbra (Portugal); Berlin (Germany); and Larnaca (Cyprus). All opaque components of the room were considered as adiabatic, excluding the front wall (3.60 m × 2.80 m) in which the window is installed. Additional details regarding the reference room are presented in Ref. [26]. The use of a reference building model allows to easily compare the results with similar studies [39].

The characteristics and dimensions of windows (i.e. thermal transmittance value, solar factor, window-to-wall ratio, orientation), as well as operation-related parameters (number of occupants and ventilation rate) are the selected design variables to be assessed in the sensitivity analysis to identify the most influential parameters of the environmental and cost performance of windows for each climate. A specific range of values for window characteristics and options (thermal transmittance, solar factor, WWR, orientation) was defined based on market availability and design possibilities. The occupancy range for the sensitivity analysis was identified based on the minimum and maximum number of occupants permitted for an office room with almost 20 m^2. Ventilation rate values were selected for calculation in single office areas according to EN 15251 (2007) [40] and EN 16798–3 (2017) [41]. The alternative locations represents different European climate zones according to the Köppen-Geiger classification system [42,43]: Portugal (Coimbra) as a temperate climate with Mediterranean hot summer (Csa); Cyprus (Larnaca) as a semi-arid (steppe) desert climate (BSh); and

Table 1
Definition of selected window- and operation-related parameters.

Parameters	Description
Location (Heating Degree Days)	Coimbra (1304), Berlin (3155), Larnaca (759)
Window orientation	South, West, North, East
WWR (%)	20, 50, 80
Window U-value (W/m^2K)	Low (U: 0.96), High (U: 2.56)
Window g-value	Low (g: 0.35), High (g: 0.78)
Number of occupants	0, 1, 2
Ventilation rate (h^{-1})	0.4, 0.8

Germany (Berlin) as a temperate oceanic climate (Cfb). Table 1 shows the window- and operation-related parameters selected for this analysis.

For the purpose of this analysis, the functional unit is the total office useful area (19.80 m^2) over a period of 30 years. The life-cycle model included the construction phase (for the wall with alternative windows) and operation phase (heating and cooling). The construction phase of the wall with alternative windows consists of raw material extraction and transport to the production site, production of the materials and their transport to the building site by lorry [44]. Technical data of the windows was taken from producers and suppliers, and relevant environmental product declarations (EPDs) presented by Saint-Gobain Glass [45]. Argon gas was considered to fill the spaces between glass panes.

The operation phase of the alternative windows covers both heating and cooling energy needs which have been calculated on an hourly basis using EnergyPlus™ [46]. GenOpt [47] was used to automate EnergyPlus™ runs. The interior seasonal heating and cooling setpoints were considered as 20 °C and 25 °C, respectively. Ensuring the energy efficiency class of A [48], a seasonal coefficient of performance (SCOP) of 3.40 and seasonal energy efficiency ratio (SEER) of 5.10 were considered for the heating and cooling, respectively. Secondary data for the Portuguese electricity mix was based on Garcia et al. [49]. While for Germany and Cyprus, secondary data was based on Ecoinvent v.3.2. database [50] due to the lack of specific data for these locations.

2.2. Environmental and cost life-cycle assessment methods

LCA addresses the potential environmental life-cycle impacts and consists of four interrelated phases: goal and scope definition, life-cycle inventory (LCI) (presented in previous subsection), life-cycle impact assessment (LCIA) and interpretation, as defined by the ISO 14040 (2006) [51] and ISO 14044 (2006) [52] standards. Global warming impact category (GW, time horizon of 100 years) calculated using the IPCC method [53] was selected. The relevance of global warming as a key performance indicator is in line with various international agreements, and more recently, the Paris Agreement commitment to achieve carbon neutrality. The LCA model and calculations have been performed using the SimaPro software.

The life cycle cost method was carried out for alternative windows to calculate the global cost in terms of net present value, considering the construction costs (initial investment for the wall with alternative windows) and operational energy costs (including both heating and cooling). The global cost was calculated based on the present value of the initial investment costs and operation costs, following the Commission Delegated Regulation (EU) No 244 [54]. The average discount rate of 3% was considered representing the current trend in Europe [55]. The initial investment costs for the wall and window solutions were gathered from manufactures and suppliers. The electricity costs were obtained from the European electricity price statistics for the three European climate zones [56].

2.3. Sensitivity analysis method and scenarios definition

The selection of sensitivity analysis methods is based on input data requirements, output type, and calculation time [56,57], as well as data availability and magnitude of data uncertainties [12]. Global sensitivity analysis have been widely used in LCA studies to quantify the contribution of each input parameter to the output variance [12,36]. Three global sensitivity analysis methods have been commonly used, namely Standardized Regression Coefficient (SRC), Spearman Correlation Coefficient (SCC), and Sobol' indices [12,58]. For case-studies with small input uncertainties (as the one presented in this article), SRC methods have been identified as having the best performance [12]. Regression-based methods have also been commonly employed for sensitivity analysis in building performance studies [22,23,59–62]. Following that, the Standardized regression coefficient (SRC) was used to identify and rank the most influential parameters of the environmental and cost performance of windows.

The correlation between model output and input parameters can be estimated in a linear regression form using the following equation:

$$y = a_0 + \sum_{i=1}^{n} (a_i . x_i + \varepsilon) \tag{1}$$

where y is the model output (life-cycle costs or GW impacts), x_i is the ith input parameter (window- and operation-related variables), n is the number of selected input parameters, a_i is the estimated regression coefficient for each x_i, a_0 is the intercept, and ε is the residual error. After standardizing, Equation (1) can be modified as follows:

$$(y - \overline{y}) \Big/ S_y = \sum_{i=1}^{n} \left(a_i . \left(S_{x_i} / S_y\right)\right)\left(\left(x_i - x_i\right) / S_{x_i}\right) \tag{2}$$

$$SRC(x_i) = a_i . \left(S_{x_i} / S_y\right) \tag{3}$$

where y is the average value of model output, x is the average value of the ith input parameter, S_y is the standard deviation of the model output, S_{xi} is the standard deviation of the ith input parameter, and SRC (x_i) is the standardized regression coefficient (SRC) of the ith input parameter.

When the selected input parameters (window- and operation-related variables) are independent of each other, the SRC can be used as a sensitivity index for quantifying the influence of altering each input parameter value from its mean by a fixed fraction of its standard deviation, whereas the values of the other parameters remain fixed values. In addition, a higher absolute SRC value indicates that the model output is more sensitive to the specific input parameter. This regression-based method has been deemed as a robust approach for sensitivity analysis [63].

To investigate the ranking of the window- and operation-related variables in each climate, a set of preliminary sensitivity analyses are performed sequentially in a way that the variable which presents the highest influence on environmental life-cycle impacts (the same for the life-cycle costs) is refined to be assessed in the subsequent analyses. For the purpose of this study, four iterations (with a set of scenarios) were presented considering three alternative locations (Portugal, Germany and Cyprus) and four alternative window orientations (North, East, South and West). Firstly, a sensitivity analysis has been performed to assess the influence of window orientation in different locations (Table 2a). This first preliminary analysis demonstrated that WWR appears as the most influential parameter for the cost and environmental life-cycle impacts considering all orientations and locations. Based on this analysis, a second set of scenarios (Table 2b) assessed the influence of WWR, revealing that the solar factor (g-value) is the second most influential parameter in warmer climates (Coimbra and Larnaca), and thermal transmittance (U-value) in a colder climate (Berlin). Hence, a third set of scenarios has been characterized differently for the alternative locations. Regarding Coimbra and Larnaca, a third set of scenarios assessed the influence of solar factor (Table 2c$_1$), while for Berlin evaluated the influence of thermal transmittance (Table 2c$_2$). Next, a fourth set of scenarios in Coimbra and Larnaca assessed the influence of U-value (Table 2d$_1$), but the influence of ventilation rate in Berlin (Table 2d$_2$). This sequential analysis allows us to identify the key drivers of environmental and cost performance of windows, as well as their ranking dependent on location and window orientation.

SRC values range from −1 to 1, to enable the identification of the key parameters with the highest influence on the environmental and cost performance of windows. A greater number implies a stronger relationship between the input parameter and the cost or environmental life-cycle impact result. Positive correlation coefficients indicate that an increase of a parameter will cause an increase in the respective cost and environmental LCA result, and negative correlation coefficients will cause a reduction of cost and environmental LCA result. Negative correlations have beneficial effects on environmental performance results (reduced environmental impact) and economic performance results (reduced global costs).

3. Results and discussions

The standardized regression coefficient (SRC) results for the sequential set of analyses are presented in this section. Section 3.1 presents the results for the first set of scenarios where the influence of variables on the environmental and cost LCA of windows have been assessed for four window orientations in three alternative locations. Section 3.2 presents the results for the second set of scenarios, after WWR has been selected as the most influential variable. Section 3.3 presents the results for the third sets of scenarios where the influence of solar factor has been evaluated for warmer climates (Coimbra and Larnaca), and thermal transmittance values

Table 2
Sequential set of scenarios with refined input parameters for alternative window orientations and three locations (Coimbra, Berlin, Larnaca).

(a) First set of scenarios (12 scenarios)				
Location (HDD)	Window orientation			
Coimbra (1304)	North			
Berlin (3155)	East			
Larnaca (759)	South			
	West			
(b) Second set of scenarios: window-to-wall ratio (36 scenarios)				
Location (HDD)	Window orientation	WWR		
Coimbra (1304)	North	0.2		
Berlin (3155)	East	0.5		
Larnaca (759)	South	0.8		
	West			
(c$_1$) Third set of scenarios in Coimbra and Larnaca: solar factor (16 scenarios)				
Location (HDD)	Window orientation	WWR	g-value	
Coimbra (1304)	North	0.2	Low (g: 0.35)	
Larnaca (759)	East		High (g: 0.78)	
	South			
	West			
(c$_2$) Third set of scenarios in Berlin: thermal transmittance value (8 scenarios)				
Location (HDD)	Window orientation	WWR	U-value (W/m^2. K)	
Berlin (3155)	North	0.2	Low (U: 0.96)	
	East		High (U: 2.56)	
	South			
	West			
(d$_1$) Fourth set of scenarios in Coimbra and Larnaca: thermal transmittance value (16 scenarios)				
Location (HDD)	Window orientation	WWR	g-value	U-value (W/m^2. K)
Coimbra (1304)	North	0.2	Low (g: 0.35)	Low (U: 0.96)
Larnaca (759)	East			High (U: 2.56)
	South			
	West			
(d$_2$) Fourth set of scenarios in Berlin: ventilation rate (8 scenarios)				
Location (HDD)	Window orientation	WWR	U-value (W/m^2. K)	Ventilation rate (h^{-1})
Berlin (3155)	North	0.2	Low (U: 0.96)	0.4
	East			0.8
	South			
	West			

for colder climate (Berlin). Section 3.4 presents the results for the fourth sets of scenarios where the influence of U-value has been assessed for Coimbra and Larnaca, and ventilation rate for Berlin. The ranking of variables has been explored for each location based on their influence on the life-cycle global warming impacts and costs. To confirm the accuracy and reliability of the numerical results, R-squared values are presented in Tables A1-A6 in the Supplementary Material. The R-squared values showed that results are statistically significant (high R-squared values).

3.1. *Influence of window orientation for three locations*

The first set of analysis include 12 scenarios combining four window orientations (North, East, South, and West) for three alternative locations defined by heating degree days (HDD): Coimbra (1304 HDD), Berlin (3155 HDD) and Larnaca (759 HDD).

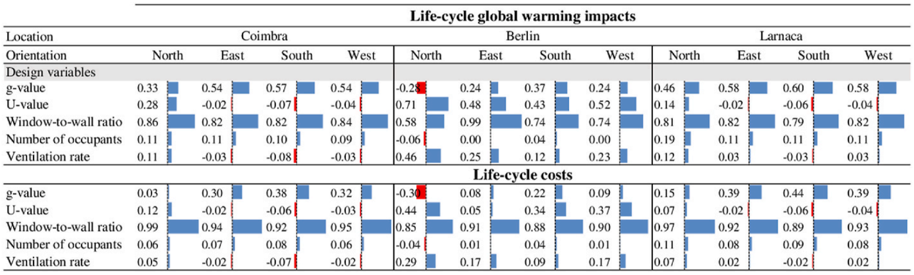
Fig. 1 depicts the standardized regression coefficient (SRC) results illustrating the relative contribution of each variable to the life-cycle global warming impacts and life-cycle costs of the 12 scenarios. Results show that the most influential variable is window-to-wall ratio (WWR) in all four orientations and three locations in terms of both life-cycle global warming impacts and costs. The second most influential parameter is the solar factor for most scenarios, with the exception of north orientation in Coimbra and Berlin (where the U-value is the second most influential) and east orientation in Berlin (where ventilation rate is the second most influential parameter). The influence of solar factor and thermal transmittance to global warming impacts is higher than to life-cycle costs, particularly in north orientation for warm climates. WWR as a top-ranked variable shows the same pattern for both GW impacts and costs. However, the higher values of standardized regression coefficient are shown by life-cycle costs than GW impacts. While regarding the next top-ranked variables (g-value in warm and U-value in cold climates), the higher values of SRCs are presented by GW impacts than costs.

Solar factor and ventilation rate present a negative correlation in north orientation in Berlin, meaning that an increase in g-value and ventilation rate leads to lower global warming impacts. While thermal transmittance value presents negative correlations in warmer locations, except for the north orientation. Ventilation rate in Coimbra has negative correlation in the life-cycle GW impacts and costs (except for the north orientation), meaning that the increase of ventilation rate leads to a decrease in GW impacts and costs. The increase of the number of occupants in north orientation in Berlin leads to a decrease in the life-cycle costs and GW impacts, as showing negative correlations. Ventilation rate and number of occupants are the variables with lower correlations in all scenarios.

3.2. *Influence of window-to-wall ratio for three locations*

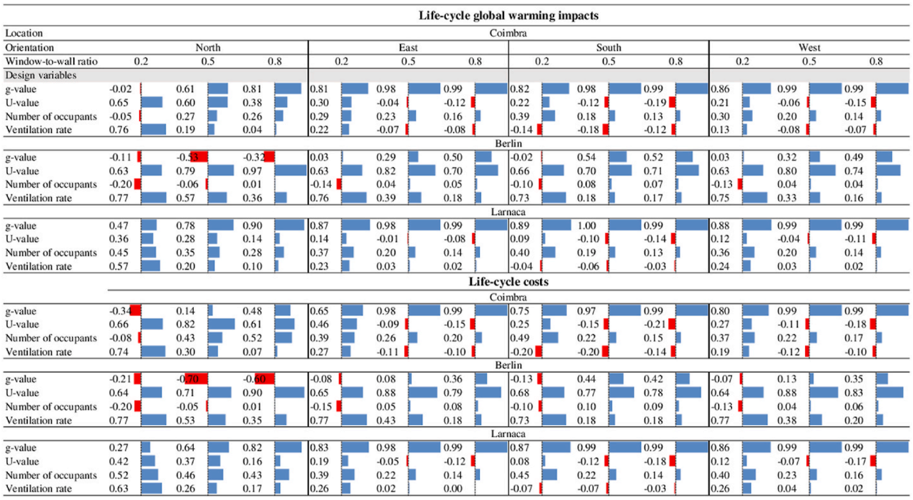
The sensitivity analysis presented in previous subsection showed that WWR appeared as the most influential variable for the life-cycle GW impacts and costs. Based on this analysis, the current subsection presents a second set of scenarios assessing the influence of WWR on the life-cycle GW and cost results. The combinations of the WWR (0.2, 0.5, 0.8) and window orientation were analyzed for each location (36 scenarios).

Fig. 2 shows the SRC results depicting the relative contribution of each variable to the life-cycle GW impacts and life-cycle costs for alternative WWR and window orientations in three locations. The results show that the most influential parameters vary depending on the location. Solar factor is the most influential parameter in terms of life-cycle GW impacts and costs in warmer climates (Coimbra and Larnaca), except for north-facing windows with a WWR of 0.2. In the cold climate (Berlin), U-value is the most influential parameter. However, there are some scenarios where the ventilation rate is the parameter more relevant (slightly higher than the U-value). Solar factor and number of occupants show a negative correlation for smaller windows (WWR of 0.2) in the cold climate of Berlin, while it presents a positive correlation for larger windows. In windows with low WWR (lower solar heat gains), higher solar factors and number of occupants lead to a decrease in heating energy needs and consequent decrease in the life-cycle GW impacts and costs. On the other hand, higher WWR (higher solar heat gains) leads to higher heating energy needs and consequently higher GW impacts and costs, with the exception of the north orientation where there are almost no solar heat gains. Window U-value is more influential in colder climates than in warmer climates due to the higher energy needs. In cold climates, such as Berlin, the higher thermal transmittance value leads to more heating energy needs and in the case of larger windows has a more significant influence to increase GW and costs. While in warmer climates (Coimbra and Larnaca), higher thermal transmittance value leads to less cooling energy needs having less significant influence in small windows to promote a decrease in GW and costs. Ventilation rate presents higher influence in lower WWRs regarding all orientations and locations. In a cold climate, the number of occupants shows negative correlation with lower WWRs. In addition, the positive correlation of solar factor with life-cycle GW impacts and costs is higher as window area increases in cold climate, excluding the north orientation which presents negative correlation.



Location	Coimbra				Berlin				Larnaca			
Orientation	North	East	South	West	North	East	South	West	North	East	South	West
Life-cycle global warming impacts												
Design variables												
g-value	0.33	0.54	0.57	0.54	-0.28	0.24	0.37	0.24	0.46	0.58	0.60	0.58
U-value	0.28	-0.02	-0.07	-0.04	0.71	0.48	0.43	0.52	0.14	-0.02	-0.06	-0.04
Window-to-wall ratio	0.86	0.82	0.82	0.84	0.58	0.99	0.74	0.74	0.81	0.82	0.79	0.82
Number of occupants	0.11	0.11	0.10	0.09	-0.06	0.00	0.04	0.00	0.19	0.11	0.11	0.11
Ventilation rate	0.11	-0.03	-0.08	-0.03	0.46	0.25	0.12	0.23	0.12	0.03	-0.03	0.03
Life-cycle costs												
g-value	0.03	0.30	0.38	0.32	-0.30	0.08	0.22	0.09	0.15	0.39	0.44	0.39
U-value	0.12	-0.02	-0.06	-0.03	0.44	0.05	0.34	0.37	0.07	-0.02	-0.06	-0.04
Window-to-wall ratio	0.99	0.94	0.92	0.95	0.85	0.91	0.88	0.90	0.97	0.92	0.89	0.93
Number of occupants	0.06	0.07	0.08	0.06	-0.04	0.01	0.04	0.01	0.11	0.08	0.09	0.08
Ventilation rate	0.05	-0.02	-0.07	-0.02	0.29	0.17	0.09	0.17	0.07	0.02	-0.02	0.02

Fig. 1. Standardized regression coefficient (SRC) depicting the relative contribution of each variable in the alteration of life-cycle global warming impacts and life-cycle costs for alternative window orientations in three locations. Each bar ranges from −1 to 1. Red bars represent negative correlation and blue bars represent positive correlation. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)



Life-cycle global warming impacts												
Location	Coimbra											
Orientation	North			East			South			West		
Window-to-wall ratio	0.2	0.5	0.8	0.2	0.5	0.8	0.2	0.5	0.8	0.2	0.5	0.8
Design variables												
g-value	-0.02	0.61	0.81	0.81	0.98	0.99	0.82	0.98	0.99	0.86	0.99	0.99
U-value	0.65	0.60	0.38	0.30	-0.04	-0.12	0.22	-0.12	-0.19	0.21	-0.06	-0.15
Number of occupants	-0.05	0.27	0.26	0.29	0.23	0.16	0.39	0.18	0.13	0.30	0.20	0.14
Ventilation rate	0.76	0.19	0.04	0.22	-0.07	-0.08	-0.14	-0.18	-0.12	0.13	-0.08	-0.07
Berlin												
g-value	-0.11	-0.53	-0.32	0.03	0.29	0.50	-0.02	0.54	0.52	0.03	0.32	0.49
U-value	0.63	0.79	0.97	0.63	0.82	0.70	0.66	0.70	0.71	0.63	0.80	0.74
Number of occupants	-0.20	-0.06	0.01	-0.14	0.04	0.05	-0.10	0.08	0.07	-0.13	0.04	0.04
Ventilation rate	0.77	0.57	0.36	0.76	0.39	0.18	0.73	0.18	0.17	0.75	0.33	0.16
Larnaca												
g-value	0.47	0.78	0.90	0.87	0.98	0.99	0.89	1.00	0.99	0.88	0.99	0.99
U-value	0.36	0.28	0.14	0.14	-0.01	-0.08	0.09	-0.10	-0.14	0.12	-0.04	-0.11
Number of occupants	0.45	0.35	0.28	0.37	0.20	0.14	0.40	0.19	0.13	0.36	0.20	0.14
Ventilation rate	0.57	0.20	0.10	0.23	0.03	0.02	-0.04	-0.06	-0.03	0.24	0.03	0.02
Life-cycle costs												
Coimbra												
g-value	-0.34	0.14	0.48	0.65	0.98	0.99	0.75	0.97	0.99	0.80	0.99	0.99
U-value	0.66	0.82	0.61	0.46	-0.09	-0.15	0.25	-0.15	-0.21	0.27	-0.11	-0.18
Number of occupants	-0.08	0.43	0.52	0.39	0.26	0.20	0.49	0.22	0.15	0.37	0.22	0.17
Ventilation rate	0.74	0.30	0.07	0.27	-0.11	-0.10	-0.20	-0.20	-0.14	0.19	-0.12	-0.10
Berlin												
g-value	-0.21	-0.70	-0.60	-0.08	0.08	0.36	-0.13	0.44	0.42	-0.07	0.13	0.35
U-value	0.64	0.71	0.90	0.65	0.88	0.79	0.68	0.77	0.78	0.64	0.88	0.83
Number of occupants	-0.20	-0.05	0.01	-0.15	0.05	0.08	-0.10	0.10	0.09	-0.13	0.04	0.06
Ventilation rate	0.77	0.53	0.35	0.77	0.43	0.18	0.73	0.18	0.18	0.77	0.38	0.20
Larnaca												
g-value	0.27	0.64	0.82	0.83	0.98	0.99	0.87	0.99	0.99	0.86	0.99	0.99
U-value	0.42	0.37	0.16	0.19	-0.05	-0.12	0.08	-0.12	-0.18	0.12	-0.07	-0.17
Number of occupants	0.52	0.46	0.43	0.39	0.22	0.14	0.45	0.22	0.14	0.40	0.23	0.16
Ventilation rate	0.63	0.26	0.17	0.26	0.02	0.00	-0.07	-0.07	-0.03	0.26	0.04	0.02

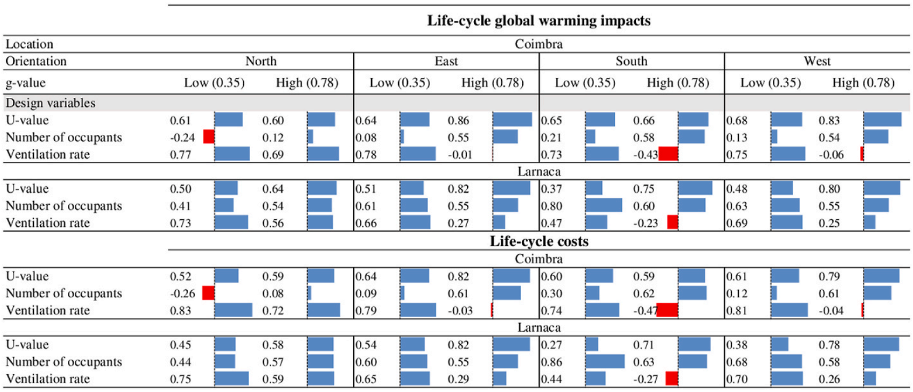
Fig. 2. Standardized regression coefficient (SRC) depicting the relative contribution of each variable in the alteration of life-cycle GW impacts and life-cycle costs for alternative window-to-wall ratios and window orientations in three locations. Each bar ranges from −1 to 1. Red bars represent negative correlation and blue bars represent positive correlation. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

3.3. *Influence of solar factor (Coimbra and Larnaca) and thermal transmittance value (Berlin)*

The sensitivity analysis presented in the previous subsection showed that the solar factor appeared as the highest influential parameter in most scenarios for the cost and GW impacts in warmer locations, while thermal transmittance value presented the highest influence in the cold climate. Based on these results, the current subsection presents a third set of scenarios (where WWR was fixed at 0.2, a standard size based on ISO 10077–1 (2017) [64]: firstly, assessing the influence of g-value on the life-cycle GW impacts and costs in Coimbra and Larnaca; and, secondly assessing the influence of U-value on the life-cycle GW impacts and costs in Berlin. For the first analysis, a set of scenarios combining a low (g: 0.35) and high (g: 0.78) solar factor for the four window orientations were analyzed in Coimbra and Larnaca (16 scenarios). While for the second analysis, a set of scenarios combining a low (U: 0.96 W/m^2. K) and high (U: 2.56 W/m^2. K) thermal transmittance value for the four window orientations in Berlin were assessed (8 scenarios).

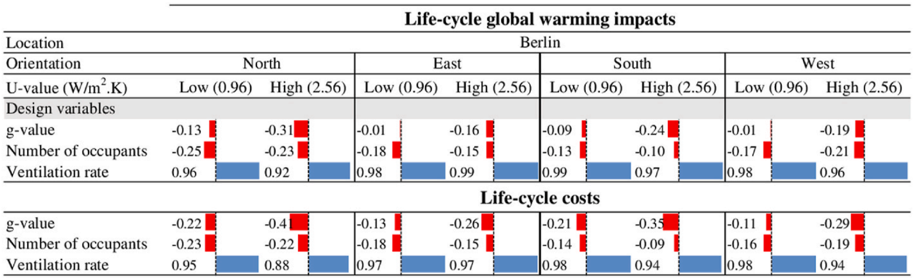
3.3.1. *Influence of solar factor in Coimbra and Larnaca*

Fig. 3 shows the SRC results depicting the contribution of each variable to the life-cycle GW impacts and costs for a set of scenarios combining alternative solar factors and window orientations, with WWR fixed at 0.2 in Coimbra and Larnaca. The results show that U-value has the highest influence in most scenarios on life-cycle global warming impacts and costs in both locations. In addition, U-value has a higher influence for higher solar factors, while the ventilation rate has a higher influence for lower solar factors, with the exception of north orientation. In Coimbra, number of occupants presents negative correlation for windows with low solar factor facing north. Ventilation rate presents a positive correlation in all scenarios, except with windows with a high solar factor facing south. U-value as a top-ranked variable presents the same pattern for both life-cycle costs and GW impacts. However, the higher values of SRCs are shown by life-cycle GW impacts than costs.



Life-cycle global warming impacts								
Location	Coimbra							
Orientation	North		East		South		West	
g-value	Low (0.35)	High (0.78)	Low (0.35)	High (0.78)	Low (0.35)	High (0.78)	Low (0.35)	High (0.78)
Design variables								
U-value	0.61	0.60	0.64	0.86	0.65	0.66	0.68	0.83
Number of occupants	-0.24	0.12	0.08	0.55	0.21	0.58	0.13	0.54
Ventilation rate	0.77	0.69	0.78	-0.01	0.73	-0.43	0.75	-0.06
Larnaca								
U-value	0.50	0.64	0.51	0.82	0.37	0.75	0.48	0.80
Number of occupants	0.41	0.54	0.61	0.55	0.80	0.60	0.63	0.55
Ventilation rate	0.73	0.56	0.66	0.27	0.47	-0.23	0.69	0.25
Life-cycle costs								
Coimbra								
U-value	0.52	0.59	0.64	0.82	0.60	0.59	0.61	0.79
Number of occupants	-0.26	0.08	0.09	0.61	0.30	0.62	0.12	0.61
Ventilation rate	0.83	0.72	0.79	-0.03	0.74	-0.47	0.81	-0.04
Larnaca								
U-value	0.45	0.58	0.54	0.82	0.27	0.71	0.38	0.78
Number of occupants	0.44	0.57	0.60	0.55	0.86	0.63	0.68	0.58
Ventilation rate	0.75	0.59	0.65	0.29	0.44	-0.27	0.70	0.26

Fig. 3. Standardized regression coefficient (SRC) depicting the relative contribution of each variable in the alteration of life-cycle GW impacts and life-cycle costs for alternative solar factors and window orientations, with window-to-wall ratio of 0.2 in Coimbra and Larnaca. Each bar ranges from −1 to 1. Red bars represent negative correlation and blue bars represent positive correlation. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)



	Life-cycle global warming impacts							
Location	Berlin							
Orientation	North		East		South		West	
U-value (W/m^2.K)	Low (0.96)	High (2.56)	Low (0.96)	High (2.56)	Low (0.96)	High (2.56)	Low (0.96)	High (2.56)
Design variables								
g-value	-0.13	-0.31	-0.01	-0.16	-0.09	-0.24	-0.01	-0.19
Number of occupants	-0.25	-0.23	-0.18	-0.15	-0.13	-0.10	-0.17	-0.21
Ventilation rate	0.96	0.92	0.98	0.99	0.99	0.97	0.98	0.96
	Life-cycle costs							
g-value	-0.22	-0.41	-0.13	-0.26	-0.21	-0.35	-0.11	-0.29
Number of occupants	-0.23	-0.22	-0.18	-0.15	-0.14	-0.09	-0.16	-0.19
Ventilation rate	0.95	0.88	0.97	0.97	0.98	0.94	0.98	0.94

Fig. 4. Standardized regression coefficient (SRC) depicting the relative contribution of each variable in the alteration of life-cycle GW impacts and life-cycle costs for alternative thermal transmittance values and window orientations, with window-to-wall ratio of 0.2 in Berlin. Each bar ranges from −1 to 1. Red bars represent negative correlation and blue bars represent positive correlation. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

3.3.2. *Influence of thermal transmittance value (U-value) in Berlin*

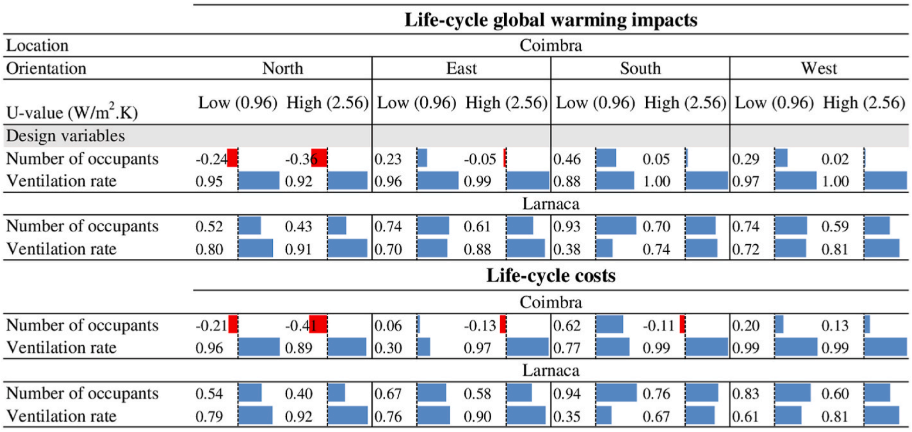
Fig. 4 shows the SRC results depicting the contribution of each variable to life-cycle GW impacts and costs for a set of scenarios combining alternative thermal transmittance values and window orientations, with WWR fixed at 0.2 in Berlin (cold climate). The results show that ventilation rate presents higher influence on the life-cycle global warming impacts and costs. Solar factor and number of occupants present a negative correlation, meaning that an increase in the solar factor and number of occupants leads to lower GW impacts.

3.4. *Influence of thermal transmittance value (Coimbra and Larnaca) and ventilation rate (Berlin)*

The sensitivity analysis presented in the previous subsection demonstrated that the thermal transmittance value appeared as the most influential parameter for the life-cycle GW impacts and costs in warmer climates, while ventilation rate presented the highest influence in the cold climate for most scenarios. Based on these results, the current subsection presents a fourth set of scenarios: firstly, assessing the influence of U-value on the life-cycle GW impacts and costs results in Coimbra and Larnaca; and, secondly assessing the influence of ventilation rate on the life-cycle GW impacts and costs results in Berlin. For the first scenario analysis (where solar factor was fixed at 0.35 due to the market demand for low solar heat gains and WWR at 0.2), a set of scenarios combining a low (U: 0.96 W/m^2. K) and high (U: 2.56 W/m^2. K) thermal transmittance value with four window orientations were analyzed in Coimbra and Larnaca (16 scenarios). While for the second analysis (where U-value was fixed at 0.96 W/m^2. K (low) towards nearly zero energy building target and WWR at 0.2), a set of scenarios combining alternative ventilation rates (0.4 and 0.8 h^{-1}) and window orientations were analyzed in Berlin (8 scenarios).

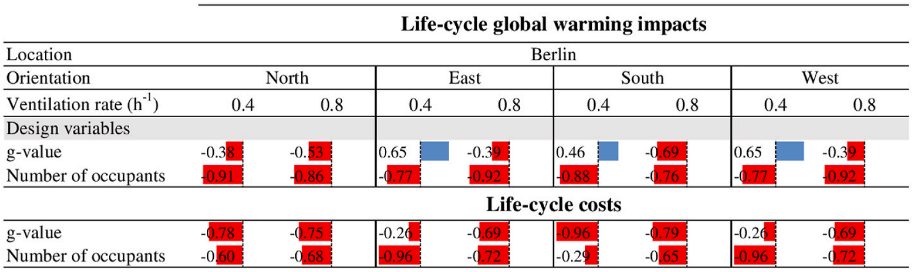
3.4.1. *Influence of thermal transmittance value in Coimbra and Larnaca*

Fig. 5 shows the SRC results depicting the contribution of each variable to life-cycle GW impacts and costs for a set of scenarios combining alternative thermal transmittance values and window orientations, with a low solar factor solution (g: 0.35) and WWR of 0.2 in Coimbra and Larnaca. The results show that ventilation rate has higher influence on the global warming impacts and costs in both locations in most scenarios, with the exception of low U-value in east, south, and west orientations for GW impacts in Larnaca



	Life-cycle global warming impacts							
Location	Coimbra							
Orientation	North		East		South		West	
U-value (W/m^2.K)	Low (0.96)	High (2.56)	Low (0.96)	High (2.56)	Low (0.96)	High (2.56)	Low (0.96)	High (2.56)
Design variables								
Number of occupants	-0.24	-0.36	0.23	-0.05	0.46	0.05	0.29	0.02
Ventilation rate	0.95	0.92	0.96	0.99	0.88	1.00	0.97	1.00
	Larnaca							
Number of occupants	0.52	0.43	0.74	0.61	0.93	0.70	0.74	0.59
Ventilation rate	0.80	0.91	0.70	0.88	0.38	0.74	0.72	0.81
	Life-cycle costs							
	Coimbra							
Number of occupants	-0.21	-0.41	0.06	-0.13	0.62	-0.11	0.20	0.13
Ventilation rate	0.96	0.89	0.30	0.97	0.77	0.99	0.99	0.99
	Larnaca							
Number of occupants	0.54	0.40	0.67	0.58	0.94	0.76	0.83	0.60
Ventilation rate	0.79	0.92	0.76	0.90	0.35	0.67	0.61	0.81

Fig. 5. Standardized regression coefficient (SRC) depicting the relative contribution of each variable in the alteration of life-cycle GW impacts and life-cycle costs for alternative thermal transmittance values and window orientations, with low solar factor solutions (g-value: 0.35) and window-to-wall ratio of 0.2 in Coimbra and Larnaca. Each bar ranges from −1 to 1. Red bars represent negative correlation and blue bars represent positive correlation. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)



	Life-cycle global warming impacts							
Location	Berlin							
Orientation	North		East		South		West	
Ventilation rate (h^{-1})	0.4	0.8	0.4	0.8	0.4	0.8	0.4	0.8
Design variables								
g-value	-0.38	-0.53	0.65	-0.39	0.46	-0.69	0.65	-0.39
Number of occupants	-0.91	-0.86	-0.77	-0.92	-0.88	-0.76	-0.77	-0.92
	Life-cycle costs							
g-value	-0.78	-0.75	-0.26	-0.69	-0.96	-0.79	-0.26	-0.69
Number of occupants	-0.60	-0.68	-0.96	-0.72	-0.29	-0.65	-0.96	-0.72

Fig. 6. Standardized regression coefficient (SRC) depicting the relative contribution of each variable in the alteration of life-cycle GW impacts and life-cycle costs for alternative ventilation rates and window orientations, with low thermal transmittance solutions (U-value: 0.96 W/m^2. K) and window-to-wall ratio of 0.2 in Berlin. Each bar ranges from −1 to 1. Red bars represent negative correlation and blue bars represent positive correlation. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

(where the number of occupants has higher influence). Regarding costs, the ventilation rate has also a higher influence in both locations in most scenarios, with the exception of south orientation and west orientation with a low U-value in Larnaca (where again the number of occupants has higher influence). In Coimbra, number of occupants presents higher positive correlation in windows with low thermal transmittance, except in north orientation, which presents a negative correlation. In Larnaca, number of occupants presents a high positive correlation in all scenarios. Higher thermal transmittance in Coimbra (particularly south orientation) combined with a high number of occupants leads to a decrease in costs while increases GW impacts.

3.4.2. Influence of ventilation rate in Berlin

Fig. 6 shows the SRC results depicting the contribution of each variable to life-cycle GW impacts and costs for a set of scenarios combining alternative ventilation rates and window orientations, with the U-value fixed at 0.96 W/m^2. K and WWR fixed at 0.2 in Berlin. The results show that number of occupants presents the highest influence (with a negative correlation) on the life-cycle global warming impacts and costs in Berlin in all scenarios, meaning that an increase in the number of occupants lead to a decrease in both GW and costs. Solar factor shows a negative correlation in the high ventilation rate (0.8 h^{-1}) scenarios (and in most low ventilation scenarios), meaning that an increase in solar factor leads to lower GW impacts and costs. Lower ventilation rates combined with high solar factors leads to a decrease in costs while increases GW impacts (with the exception of north orientation).

4. Conclusions

The main goal of this article was to perform a sensitivity analysis to identify the key drivers and rank the input parameters which contribute the most to variability of global warming and life-cycle costs of windows for three European locations in different climate regions. A set of alternative window configurations combining window-related parameters (i.e. thermal transmittance value, solar factor, window-to-wall ratio, orientation), as well as varying operation-related parameters (i.e. number of occupants and ventilation rate), were investigated in three selected European locations (Coimbra, Berlin and Larnaca). The sensitivity analysis was employed by calculating the standardized regression coefficient (SRC) method.

Results show that the key driver for global warming and cost was window-to-wall ratio in all window orientations and locations. Thermal transmittance value (U-value) has a higher influence in smaller windows in warmer climates (Coimbra and Larnaca), while in bigger windows it is more influential in colder climates (Berlin). In addition, ventilation rate has a high influence (with a positive correlation) in smaller windows in Berlin, meaning that an increase of ventilation rate leads to an increase of cost and global warming. In Berlin, the positive correlation of solar factor becomes higher as window area increases (excluding the north orientation), meaning that the increase of solar factor in bigger windows leads to the increase of cost and global warming.

Solar factor was identified as the secondly most influential parameter in warmer locations. In contrast, thermal transmittance value was identified as the second most influential parameter in cold climates. However, the influence of solar factor and thermal transmittance value on the global warming impacts is higher than the life-cycle costs, particularly in north orientation for warm climates. In Berlin, solar factor and number of occupants have negative correlation in smaller windows, meaning that an increase of these parameters leads to lower global warming impacts.

This article provides recommendations for the selection of windows to promote lower life-cycle impacts (global warming and costs) of windows in warm and cold climate locations in Europe. The results primarily suggest the selection of smaller windows in warmer climates; however, if the building design wants to promote daylight and a good view, bigger windows with lower solar factors can be selected. In cold climates, bigger windows should be employed, unless the building design requires smaller windows then high solar factors are recommended. Moreover, a low thermal transmittance value is suggested for cold climates, while it is recommended for warm climates only in north-oriented windows. In case of office rooms with a high ventilation rate, windows with high solar factors should be selected for cold climates, and south-oriented windows for warmer climates. The identification of key influential parameters and their ranking is important to support the environmental and cost life-cycle assessment at early-design stages, when a window design is most flexible and more informed decisions can be made to promote lower life-cycle environmental impacts and costs of buildings. Future work will focus on developing a streamlined environmental and cost LCA approach, to support the selection of windows in the early design stages of buildings. This approach aims to reduce the uncertainty in the estimated results by means of sequentially specifying attributes based on a quantified attribute ranking presented in this article.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jobe.2022.104206.

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