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INTEGRATED COST AND ENVIRONMENTAL LIFE CYCLE ANALYSIS OF WINDOWS

PhD thesis in Sustainable Energy Systems,
supervised by Professors:
Fausto Miguel Cereja Seixas Freire
Professor Nuno Albino Vieira Simões
presented to the Department of Mechanical Engineering,
Faculty of Sciences and Technology, University of Coimbra

December 2021

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- *In memory of my late father (Mohammad Ali) who taught me to be an independent and determined person,*
- *To my doting mother (Masih) without whom I would have never been able to achieve my objectives and succeed in life.*

Acknowledgements

I would sincerely like to thank the many people who supported me during my PhD preparation, to only some of whom it is possible to give a particular mention here.

To my supervisors: professor Fausto Freire and professor Nuno Simões for the opportunity to develop this thesis, for their support, guidance, and encouragement.

To the Energy for Sustainability Initiative of the University of Coimbra (EfS-UC), Associação para o Desenvolvimento da Aerodinâmica Industrial (ADAI), and the MIT-Portugal Program for their support provided during this work.

To Carla Rodrigues, for her great experience and help regarding the streamlined life cycle assessment.

To the Institute of Interdisciplinary Research at the University of Coimbra (III-UC), for providing a peaceful and enjoyable work environment for the collaborators.

To Professor Cláudia Cavadas, Vice-Rector for Research at the University of Coimbra, for her support and encouragement not only in my working area but also in my academic area.

To my colleagues from the strategic research areas of the University of Coimbra (III-UC): Clara Barata, Natacha Leite, Isabel Neves, and Maria João Neves, for their supports and friendships, especially, for contributing to a peaceful and enjoyable work environment.

To Rita Garcia, Érica Castanheira, and Pedro Marques, my colleagues from the Center for Industrial Ecology (CIE), for their supports during my journey.

To Professor Carlos Henggeler Antunes, University of Coimbra, for our helpful discussions about the Pareto optimal frontier concept.

To the Institute for Research and Technological Development for Construction, Energy, Environment and Sustainability (Itecons), for providing the data regarding the energy performance analysis.

And for those who belong to my personal life and who helped in many different ways to make this journey much easier, I am truly grateful.

To my mom and my beloved family for never questioning my decisions and being unquestionably supportive and proud.

To my brother (Mehdi) and my sisters (Sheida and Mahsa) who offered invaluable support and humor over the years.

To my nieces (Rojan and Lena) and nephews (Benyamin and Tiam) for always being my motivation to keep on going.

To Farhang, Aram, Abar, Juliana and Miguel, Vasco and Sonia for being my lifetime friends.

Finally, To Behrang, for all the above and beyond. Just for being there.

This research presented in this thesis was supported by the Portuguese Science and Technology Foundation (FCT) and the MIT Portugal Program through a doctoral grant through grant PD/BD/113537/2015. This research was also framed under the Energy for the Sustainability Initiative of the University of Coimbra. This research has also been supported by projects SET-LCA (CENTRO-01-0145-FEDER-030570) and T4ENERTEC (POCI-01-0145-FEDER-029820), co-funded by FEDER and FCT, and by the project EvoSlide (POCI-01-0247-FEDER-033658) and CorkAl (POCI-01-0247-FEDER-033814) funded by Portugal 2020 through COMPETE2020.

Cofinanciado por:

Abstract

There is an increasing need for energy-efficient windows; but these windows can have high embodied impacts and can be costly. Hence, it is important to wisely select optimal windows that minimize energy consumption, costs, and environmental impacts throughout their life cycle. However, life cycle assessments (LCAs) are time-consuming and resource-intensive, and usually performed at late-design stages when the potential to make changes is low. The selection of windows with the lowest life cycle cost (LCC) and environmental impacts in an early-design stage can potentially minimize the environmental impacts and costs of buildings. Thus, it is important to streamline LCA and LCC of windows to support early-stage building design decisions.

The main goal of this PhD thesis is to investigate both full and streamlined LCA approaches to support the selection of windows to improve the life cycle environmental and economic sustainability of European office buildings. Firstly, an integrated cost and environmental full LCA approach combined with thermal dynamic simulation has been developed for alternative windows combining various framing materials (aluminum, fiberglass, PVC, and wood), and glazing solutions (from low to high values of thermal transmittance and solar factors). The influence of each window component, as well as window properties on the LCC and LCA has been investigated for three European climates. Operational energy, life cycle environmental impacts and costs have been assessed and trade-offs have been identified. LCC has been performed to calculate the cost in terms of net present value for the window solutions. A sensitivity analysis has been performed to rank the parameters that contribute the most to variability in LCA and LCC of windows to support the development of a streamlined LCA approach.

Next, an approach has been developed to streamline LCA and LCC of windows to support early-decision making for selection of windows. This approach enables estimation of economic and environmental performance of windows with different levels of information specified. In addition, this approach may reduce the uncertainty in the estimated results by means of sequentially specifying attributes based on a quantified attribute ranking derived from the full LCA.

Some recommendations are provided to enhance the economic and environmental performance of windows in European office buildings based on the full LCA results. The optimal window solutions for warm climates highlighted low solar factor windows, while for cold climates low thermal transmittance solutions. The glazing is the component with the greatest influence on the LCA results (mainly operational). The impacts depend to a very great extent on the thermal transmittance values

and solar factors. LCC shows that the initial investment in the windows has a high impact on the overall cost, even for a lifespan of 30 years. A sensitivity analysis on a set of window solutions allowed to conclude that the highest influential parameter on LCA and LCC is window-to-wall ratio, for all orientations and locations. In addition, 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 or small windows with high solar factors. Thermal transmittance value has a large influence on smaller windows in warmer climates, while in colder climates on bigger windows.

The streamlined LCA model has proved to be effective in providing robust results to support the selection of windows, at early-design stages of buildings, by specifying very few window- and operation-related attributes (less than 8). The confidence in the results has been confirmed by comparing the results with the full LCA results. This PhD research covers a large range of windows available in the market in terms of thermal transmittance and solar factor values. Hence, future market window solutions with random values of thermal transmittance and solar factor can be assessed using this approach to promote a better cost and environmental performance of buildings. In addition, this PhD research develops a streamlined model to assess the environmental and cost performance of windows with limited inventory data about most design attributes. Following that, it is not essential to perform a time-consuming and resource-intensive full LCA to select the most appropriate window solution in terms of environmental and cost performances. The streamlined model enables designers to select window solutions that improve the life cycle cost and environmental performance of buildings, when limited information is available at an early-design stage.

Keywords: Window, solar factor, thermal transmittance, life cycle assessment, life cycle costing, sensitivity analysis, attribute ranking, early-stage decisions, streamlining, uncertainty

Resumo

Há uma necessidade crescente de usar janelas energeticamente eficientes; mas estas janelas podem ter impactes ambientais e custos elevados. Portanto, é importante selecionar janelas que minimizem o consumo de energia, custos e impactes ambientais ao longo do seu ciclo de vida. No entanto, um estudo de avaliação do ciclo de vida (ACV) requer muito tempo e recursos, e são normalmente realizados em fases finais do projeto, quando o potencial para efetuar alterações é baixo. A seleção de janelas com o menor custo de ciclo de vida (CCV) e impactos ambientais numa fase inicial do projeto pode potencialmente minimizar os impactos ambientais e os custos dos edifícios. Assim, é importante agilizar a implementação da ACV e CCV de janelas para apoiar as decisões na fase inicial de conceção de edifícios.

O principal objetivo desta tese é investigar abordagens de ACV, tanto a análise completa como a agilizada, para apoiar a seleção de janelas a fim de melhorar a sustentabilidade ambiental e económica do ciclo de vida dos edifícios de serviços na Europa. Em primeiro lugar, foi desenvolvida uma abordagem de CV ambiental e económica, combinada com simulação térmica dinâmica, para janelas alternativas combinando vários materiais para a caixilharia com vários tipos de vidro. A energia operacional, os impactes ambientais do ciclo de vida e os custos foram avaliados, e foram identificados potenciais compromissos ("trade-offs"). A avaliação de CCV (ACCV) foi realizada para calcular o custo em termos de valor presente líquido para as várias opções de janelas. Foi realizada uma análise de sensibilidade para classificar os parâmetros que mais contribuem para a variabilidade na ACV e da CCV de janelas no sentido de apoiar o desenvolvimento de uma abordagem de ACV agilizada.

Adicionalmente, foi desenvolvida uma abordagem agilizada de ACV e de ACCV de janelas para apoiar a tomada de decisão na seleção de janelas em fases iniciais de projeto. Esta abordagem permite avaliar o desempenho ambiental e de custo de janelas com diferentes níveis de informação especificados. Além disso, esta abordagem permite reduzir a incerteza nos resultados estimados através da especificação sequencial de parâmetros com base numa classificação quantificada de parâmetros derivada da análise completa do CV.

Com base nos resultados, é possível fornecer algumas recomendações para melhorar o desempenho económico e ambiental de janelas em edifícios de serviços na Europa. As opções de janelas com melhor desempenho para climas quentes apresentam baixos fatores solares, enquanto que para climas frios, estas apresentam valores baixos de coeficiente de transmissão térmica. O tipo de vidro é o parâmetro com maior influência nos resultados da ACV (principalmente na fase de uso). A variação nos impactes depende, principalmente, do coeficiente de transmissão térmica e do fator solar. A ACCV mostra que o investimento inicial nas janelas tem um impacto elevado no custo global, mesmo durante uma vida útil de 30 anos. Uma análise de sensibilidade sobre um conjunto de opções de janelas permitiu concluir que o parâmetro de maior influência na ACV e na ACCV é a fração envidraçada da fachada ("window-to-wall ratio"), para todas as orientações e localizações. Além disso, outros parâmetros influentes dependem da localização: para climas mais quentes, recomenda-se janelas mais pequenas ou janelas maiores com fatores solares baixos; para climas mais frios, janelas maiores ou janelas pequenas com fatores solares altos.

O modelo para a ACV agilizada de janelas provou ser eficaz no cálculo de resultados robustos para apoiar a seleção de janelas, em fases iniciais de conceção dos edifícios, especificando muito poucos parâmetros, tanto relacionados com a configuração das janelas como de utilização dos edifícios (menos de 8). A confiança nos resultados da ACV agilizada foi confirmada pela comparação dos resultados com os resultados da análise completa. Esta tese de doutoramento avalia uma vasta gama de janelas disponíveis no mercado em termos de coeficiente de transmissão térmica e fator solar. Esta tese de doutoramento desenvolveu um modelo agilizado para avaliar o desempenho ambiental e de custos de janelas com dados de inventário limitados. Assim, esta abordagem permite avaliar futuras opções de janelas no mercado com uma vasta gama de valores de coeficiente de transmissão térmica e fator solar para promover um melhor desempenho ambiental e de custo dos edifícios, não sendo essencial realizar uma análise completa, demorada e intensiva em recursos, para selecionar a solução de janelas com melhor desempenho ambiental e de custo de ciclo de vida. O modelo agilizado permite aos engenheiros e arquitetos selecionar as opções de janelas que melhoram o desempenho ambiental e de custo de ciclo de vidados edifícios, com pouca informação disponível numa fase inicial do projeto.

Palavras-chave: Janela, fator solar, coeficiente de transmissão térmica, avaliação de ciclo de vida, avaliação de custo de ciclo de vida, análise de sensibilidade, classificação de parâmetros, decisões em fase inicial de projeto, abordagem agilizada, incerteza

Table of contents

List of figures

List of tables

Acronyms, abbreviations and symbols

AAM: Attribute to activity model

AC: Acidification

ALU: Aluminum

ALU.D: Aluminum frame for double-glazing

ALU.S: Aluminum frame for single-glazing

ALU.T: Aluminum frame for triple-glazing

A_n: Annealed glass type

BAIA: Building Attribute to Impact Algorithm

CC: Climate change

CED: Cumulative energy demand

CEN: European Committee for standardization

CI: Comparison indicator

CO_2: Carbon dioxide

D: Double glazing

DA: Double A glazing solution

DB: Double B glazing solution

DC: Double C glazing solution

DD: Double D glazing solution

EE: Embodied energy

EPBD: Energy Performance of Buildings Directive

EU: Eutrophication

EW: Exterior wall

FGL: Fiberglass

FGL.DT: Fiberglass frame for double- and triple-glazing

FGL.SD: Fiberglass frame for single- and double-glazing

FU: Functional unit

g: Solar factor

GC: Global cost

GW: Global warming

HDD: Heating degree days

HVAC: Heating, ventilation, and air-conditioning

ISO: International Standardization Organization

L_a: Laminated glass type

LCA: Life cycle assessment

LCC: Life cycle cost

LEED: Leadership in Energy and Environmental Design

LCI: Life cycle inventory

LCIA: Life cycle impact assessment

MW: Mineral wool

NPV: Net present value

NRPE: Non-renewable primary energy

OD: Ozone layer depletion

PVB: Polyynyl Butyral

PVC: Polyvinyl chloride

PVC.D: PVC frame for double-glazing

PVC.S: PVC frame for single-glazing

PVC.T: PVC frame for triple-glazing

$\mathbf{Q_C}$**:** Cooling energy needs

$\mathbf{Q_{C,ref}}$**:** Reference value for cooling energy needs

$\mathbf{Q_H}$**:** Heating energy needs

$\mathbf{Q_{H,ref}}$**:** Reference value for heating energy needs

$\mathbf{r_{QC}}$**:** Cooling ratio

$\mathbf{r_{QH}}$**:** Heating ratio

S: Single glazing

SA: Single A glazing solution

SB: Single B glazing solution

SC: Solar control

SCOP: Seasonal coefficient of performance

SD: Standard deviation

SEER: Seasonal efficiency ratio

SRC: Standardized Regression Coefficients

T: Triple glazing

TA: Triple A glazing solution

TB: Triple B glazing solution

$\mathbf{T_e}$**:** Tempered glass type

U: Thermal transmittance value

WOO: Wood

WOO.SDT: Wood frame for single-, double- and triple-glazing

$\succ$: dominates

$\forall$: for all

$\exists$: there exists

$\wedge$: and

1. Introduction

1.1 Background and motivation

Nearly half of the European Union's final energy consumption is used for heating and cooling, of which 80% is consumed by buildings (European Commission, 2021a). The European Commission established an objective of "energy efficiency first principle"; i.e. considering the greatest cost-efficient energy efficiency measures in forming energy policy and making appropriate investment decisions. In building design, this target should be accomplished by suitable assessment of energy-efficient building components in cost-benefit analysis and impact assessments (European Commission, 2021b).

Windows are one of the most challenging building components as they are complex systems with various elements, materials, quantities, and very specific properties. In addition, the embodied impacts of window materials can be considered as hidden impacts, away from the construction site and not visible to the user, but they are increasingly significant as buildings become more energy efficient (Finnegan et al., 2018; Seo et al., 2018). Embodied impacts of window materials are the sum of impacts required in the production and transportation, from raw material extraction to the building site, i.e. from 'cradle-to-site' (Tavares et al., 2019). Research and policy strategies have been focusing on reducing a building's operational energy (Kirankumar et al., 2020; Malmqvist et al., 2018), while the embodied impacts of building materials have been overlooked. Basbagill et al. (2013) highlighted the importance of addressing the embodied impacts of the building materials when improving the energy efficiency of buildings. A reduction of operational impacts is normally associated with a rise in the contribution of embodied impacts related to building materials (Rodrigues and Freire, 2017).

Followingly, windows play a crucial role not only in affecting daylight and view (Zhang et al., 2011; Zhu et al., 2013), but also in the overall energy needs of buildings (Goia, 2016; Mangkuto et al., 2016; Zhu et al., 2013), and, consequently, in the environmental and costs during a building life cycle. Furthermore, windows represent a notable material flow, as reported by one of the European window markets (Verband Fenster + Fassade) in 2012, and an estimated consumption of 73.2 million units (1.3m×1.3m) throughout the 27 EU member states (Souviron et al., 2019). Hence, it is essential to select appropriate windows for buildings to decrease energy consumption and environmental impacts. To influence those window selections in a manner that reduces the overall burdens, it is very important to consider a life cycle perspective. Life cycle assessment has commonly been applied to estimate the environmental impacts of building components, to find out the hot spots, and enhancement opportunities for each life cycle phase (Rebitzer et al., 2004).

However, there are challenges in the building design when selecting a window, for instance, defining the best window size to promote, at the same time, natural light and low heating and cooling needs. These challenges can be more complex when combining environmental and cost LCA of windows, realizing that, to promote low-cost and environmentally friendly windows, numerous parameters need to be defined, with a contradictory nature between themselves (Alanne et al., 2007; ALwaer and Clements-Croome, 2010; Grynning et al., 2013). Trade-offs can be identified in the definition of window parameters, 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 the early-design stage of buildings which attributes 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 (Heijungs, 1996; Kristensen and Petersen, 2016), as well as to support the development of a streamlined LCA approach. Hence, window attributes can be selected at the early stage of a building design, such as type, area, thermal transmittance value, solar factor, and orientation of windows, as they highly influence the environmental and economic performance of buildings (Hester et al., 2017).

Detailed data inventory is a critical step for life cycle assessment (LCA) due to the impact on the results. This issue is particularly challenging at the early stages of design when specific and reliable data is not available. In addition, LCAs are usually performed at late-design stages (Rodrigues et al., 2018), when most decisions have already been made and the potential to make changes is low (Meex et al., 2018). The selection of window materials and components with the lowest life cycle impacts and costs in an early-design stage is important to minimize the environmental impacts and costs of buildings. Thus, it is essential to identify the key drivers of environmental and cost of windows to reduce the time and effort needed to perform an 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.

This thesis investigates both full and streamlined LCA approaches to support the selection of windows to improve the life cycle environmental and economic sustainability of buildings. The following subsections present a succinct state of the art and existing gaps in the literature for the integrated cost and environmental LCA of windows exploring full and streamlined LCA approaches, respectively. Additional literature reviews on each topic will be further discussed in each chapter of the thesis.

1.1.1. Integrated cost and environmental LCA of windows (full LCA)

In recent decades, the EU thermal regulations have been attempted to produce more energy-efficient window solutions because of the enhancement of the energy efficiency in buildings (Souviron et al., 2019). Much of the literature on the environmental performance of windows has paid particular attention to the environmental impacts from the operation phase (Abdul and Mohammad, 2015; Tsikaloudaki et al., 2012) and very few studies have investigated the embodied impacts of windows (Asdrubali et al., 2021; Cole and Kernan, 1996; Demertzi et al., 2017), while the environmental performance of windows through their overall life cycle has been overlooked. Therefore, there is a lack of comprehensive LCA studies assessing the environmental impacts from both production and operation phases of windows.

Decision about the type of window frame, number of pane of glasses (single, double or triple), the gas filling the cavity (e.g., air or argon), coatings (e.g., low emissivity or solar control) will influence embodied impacts. Much of the current literature on window properties tend to focus on embodied impact assessment of a single element of windows (Souviron et al., 2019), with most authors concentrating on the framing (Carlisle and Friedlander, 2016; Recio et al., 2005; Sinha and Kutnar, 2012; Tarantini et al., 2011), a few on the glazing (Asdrubali et al., 2021; Babaizadeh and Hassan, 2013; Syrrakou et al., 2005), and shading (Babaizadeh et al., 2015; Invidiata and Ghisi, 2016; Sanati and Utzinger, 2013). The rest have studied whole windows rather than addressing the embodied impacts of individual components (Baldinelli et al., 2014; Menzies and Wherrett, 2005). For example, Sinha and Kutnar (2012) assessed three framing materials (aluminum, PVC, wood) and showed that the carbon footprint for aluminum and PVC frames was respectively 4 and 2 times higher than for a wood frame. For the PVC framing system, polyvinyl chloride contributed 45% to the embodied carbon, with stainless steel contributing 25%. Regarding the aluminum framing, the main contributions to the embodied carbon were aluminum (70%) and fiberglass reinforced plastic (10%). Seo et al. (2015) also analyzed the embodied impacts of an aluminum framing solution and found that aluminum is the main contributor to the embodied carbon (87%) of a window, due to the energy used in the smelting process. Among different frame materials, fiberglass rarely has been assessed in terms of environmental performances, particularly assessing with different glazing types. For glazing solutions, Syrrakou et al. (2005) assessed the environmental impacts associated with the production of electrochromic (EC) glazing compared with various insulating glass units. The results showed that EC glazing could have lower environmental embodied impacts, plus lower cost, and better thermal and optical behavior.

From the above literature review, we have concluded that there are few studies addressing the embodied impacts of individual components of windows (glazing and framing and their constituents), and it is essential to break each individual window part down into its components to determine the key contributors to the total embodied impacts. In addition, there have been no comparative studies on the embodied impact assessment of windows which investigate the influence of thermal transmittance and solar factors, together with the effect of individual constituents of glazing and framing options on the total embodied impacts of a window solution. The enhancement of window designs has been mainly focused on mechanical, architectural, thermal, and acoustical aspects; however, environmental impacts are increasingly important and embodied impacts have not been thoroughly assessed.

Thermal transmittance value (U-value) and solar factor (g-value) are the properties with an important role in the energy balance of windows. However, research on the influence of the window properties has mainly focused on the operational energy performance of windows (Tsikaloudaki et al., 2012; Yeom et al., 2020), overlooking life cycle environmental impacts and costs.

Much of the literature on the environmental performance of windows has paid particular attention to the environmental impacts in the operation phase (Litti et al., 2018; Papaefthimiou et al., 2009) and few studies have investigated the embodied impacts of windows (Seo et al., 2015; Sinha and Kutnar, 2012), while the environmental performance of windows over their complete life cycle has been overlooked. Several attempts have been made, however, to investigate the economic performance of windows without looking at the environmental performance. Menzies and Wherrett (2005) investigated the energy and cost savings that might be achieved in the design and selection of sustainable multi-glazed windows. Jaber and Ajib (2011) identified the optimum window type and size to reduce both energy and investment costs for three climate zones (Amman, Aqaba, and Berlin).

Environmental and cost life cycle assessment can be integrated to explore the most influential window properties (U- and g-value) and components (glass and frames) in terms of the economic and environmental performance and to estimate the environmental and cost benefits of the window solutions. So far, Minne et al. (2015) applied an integrated environmental and cost life cycle analysis to alternative windows for a single-family home in various US climate regions. However, the contribution of individual window components (glass and frames), as well as the influence of window properties (U- and g-value) to the life cycle cost and environmental impacts have not been presented. A great gap still exists for the full environmental and cost LCA of windows investigating the influence of both window properties and components for different climates.

Along with the thermal transmittance and solar factor for windows, orientation, and climate data are significant factors for the life cycle cost and environmental impacts of a window (Banihashemi et al., 2015; Burgett et al., 2013). A considerable amount of literature has studied the effect of window orientation and climatic conditions on the operational performance of buildings (lighting, heating, and cooling load). Mangkuto et al. (2016) investigated the influence of window area and orientation on the various daylight metrics and lighting energy demand in buildings. The results showed that the optimal window solutions in terms of daylight metrics and lighting energy demands were South-facing windows with about 30% window-to-wall ratio. Alghoul et al. (2017) assessed the influence of window area and orientation on the heating and cooling energy consumption of an office in Libya. Some studies have also looked to the life cycle cost. For example, Pikas et al. (2014) considered possible window design solutions and orientations for the office buildings in the cold Estonian climate, taking both cost optimality and energy efficiency into account. Yasar and Kalfa (2012) used energy simulation software to investigate the effects of different glazed units and orientations on the energy needs and operating cost of high-rise residential buildings in moderate-humid climate regions of Turkey.

The operational stage is generally the main contributor to the total life cycle impacts; however, for getting windows more energy-efficient, the contribution of embodied impacts increases. This aspect has not been thoroughly analyzed and as mentioned before, the literature has mainly focused on the operational performance of windows. Furthermore, there have been no comparative life cycle studies on windows that investigate the influence of high versus low U- and g-values, together with the effect of orientation and climate data on both economic and environmental life cycle assessment. Thus, a comprehensive life cycle analysis should be performed to inform the wise selection of windows, considering their properties and components.

An important gap in the literature still exists combining environmental and cost life cycle assessment of windows. An integrated assessment can provide a more comprehensive framework to select the most cost-effective and environmentally friendly solutions. Furthermore, the trade-offs between cost and environmental impacts can be addressed using a bi-objective optimization (costs vs. environmental impacts).

Sensitivity analysis in life cycle assessment of windows

Sensitivity analysis is a significant tool to identify the most influential design variables in buildings' performance (Heijungs, 1996; Kristensen and Petersen, 2016). There has been an increasing amount of literature recently on sensitivity analyses of window design parameters, mainly comparing the energy performance of alternative solutions (Ma et al., 2015; Ochoa et al., 2012; Persson et al., 2006; Sharma et al., 2021; Xue et al., 2019; Zeferina et al., 2021).

However, the ranking of most influential parameters on the energy performance of buildings has not been addressed in a life cycle perspective. For example, Tavares et al. (2016) performed a sensitivity analysis to compare several window solutions and orientations with different transition range for the optical properties through incident solar radiation in terms of energy needs for space heating and cooling. Singh et al. (2016) 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 the window-to-wall ratio (WWR), glazing type, blind orientation, and slat angle. Dussault & Gosselin (2017) performed a sensitivity analysis to assess the relative effect of the main building design parameters on energy and comfort improvements related to the use of a smart window.

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 (Rodrigues and Freire, 2021). Tian and De Wilde (2011) 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 gains coefficients of windows, and cooling degree days, in charge of around 95% of the output variances. Ballarini and Corrado (2012) 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. (2008) used the 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. (2016) 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.

Both window- and operation-related parameters have been studied in the literature to compare LCA results of different window solutions; however, without detailing the influence of very specific window parameters to improve the life cycle environmental and economic sustainability of windows for the buildings. There are studies which have performed sensitivity analysis on the LCA of window solutions during the operation phase (Minne et al., 2015; Su and Zhang, 2010), but disregarding the environmental performance of windows over their entire life cycle. A notable exception is a work of Salazar (2014) who performed a sensitivity analysis of the applied datasets, 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 (Ghisi and Tinker, 2005; Lee et al., 2013; Ma et al., 2015; Persson et al., 2006; Phillips et al., 2020). For example, Lee et al. (2013) 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 the 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 (2010) have measured the environmental impacts of operational performance of various windows with WWR ranges of 10 to 70% in different orientations, for a typical Chinese 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 and typically assumed as fixed variables, 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 (Wei et al., 2015).

A sensitivity analysis can increase the robustness of the results, as well as find key drivers of the environmental and cost impacts of windows in various locations. The recognition of the key influential attributes can efficiently support the environmental and cost advice for the streamlined LCA.

1.1.2. Streamlined cost and environmental LCA of windows

Window attributes need to be selected at an early stage of a building design, such as frame and glass options, area, thermal transmittance value, solar factor, and orientation of windows, as they highly influence the environmental and cost performance of buildings (Souviron et al., 2019). However, detailed data inventory is a critical step for life cycle assessment due to the impact on the results. This issue is particularly challenging at the early stages of design when specific and reliable data is not available. In addition, LCAs are usually performed at late design stages, when most decisions have already been made and the potential to make changes is low (Meex et al., 2018). The selection of window materials and components with the lowest life cycle impacts and costs in an early-design stage is important to minimize environmental impacts and costs of buildings.

Streamlined LCA can support early-stage design decisions; however, streamlined LCA approaches applied to buildings have been mostly focused on the embodied impact assessment of materials (Asdrubali et al., 2021). Many of these streamlined LCA studies have integrated building information modeling (BIM) with other tools to translate technical drawings into a bill of materials. For example, Schlueter and Thesseling (2009) have used a BIM model to estimate the required data and parameters during the design stage, coupled with another tool enabling the estimation of the energy needs for the design varieties. Other streamlined LCA studies have used a macro component approach to identify a range of presumed construction solutions for the key components of a building, incorporating life cycle embodied data (Bribián et al., 2011; Gervásio et al., 2014; Pushkar et al., 2005). In general, these streamlined LCA approaches simplify the assessment of the life cycle environmental performance of a building with limited data, as well as support decision-making for the use of alternative construction solutions aiming to reduce energy consumption and life cycle impacts. However, none of the just mentioned streamlined LCA approaches has focused on windows.

It should be underlined that streamlined LCA approaches applied at the early-design stages of buildings have to deal with many uncertainties due to the lack of information about quantities and types of materials and activities (Galimshina et al., 2020). Streamlined LCA leads with several issues particularly concerning the robustness of the results: whether there is too much uncertainty and variation in the attribute specification, and how detailed the attributes need to be provided by the designer. Hence, it is essential to support the confidence in the results estimated by a streamlined LCA approach. These approaches have rarely addressed the uncertainty caused by the limited information at early design processes. Two exceptions are the separate works of Basbagill et al. (2013) and Rodrigues et al. (2018). Basbagill et al. (2013) presented a novel approach to estimate building embodied impacts based on different amounts of information addressing uncertainty. Sensitivity analysis was conducted on the embodied impacts of a range of building shapes and design parameters. The distribution of embodied impacts among building parameters was shown by an impact allocation scheme, and material and thickness alternatives with the greatest embodied impact reductions were presented by an impact reduction scheme. Rodrigues et al. (2018) developed a streamlined cost and environmental LCA approach to building retrofits, including uncertainty analysis to tackle the lack of information at early design processes by using the building attribute to impact algorithm approach, which includes structured under-specification and probabilistic triage.

The impact of windows in a building is highly associated with its energy behavior. To estimate the influence of windows on the energy performance of buildings at early design stages, there are energy modeling software packages helping practitioners compare the performance of window alternatives; however, these tools regularly need detailed information that is only accessible after the building design has been completed. Another limitation for window energy modeling is that it is time-consuming. COMFEN is one of the window energy modeling tools to simulate the influence of window variables on energy consumption, and thermal and visual comfort. However, designers implementing COMFEN encounter multiple design configurations forcing them to run numerous simulations which is extensively costly and time-consuming. Garg et al. (2014) developed a tool for optimizing the window configuration (WinOpt) by computing the energy consumed by the building using EnergyPlus and then optimizing the user-selected parameters by GenOpt. This tool can therefore be useful in reducing the time and cost to assess operational energy performances, yet a streamlined environmental and cost life cycle approach of alternative window solutions is lacking (Baldinelli et al., 2014). Tools are still required for providing advice on the selection of window attributes at the early stages of a building design in order to have the greatest impact on the cost and environmental performance.

Windows face different types of decisions at the early-design stages of buildings, such as which window-to-wall ratio is appropriate for each building space, or which window properties are more appropriate regarding the particular orientation and climate data. A streamlined LCA is lacking to perform an integrated environmental and cost assessment of windows, which fully integrates embodied and operational energy assessment of windows at the early stages of a building design.

This PhD thesis pursues to address these gaps by evaluating a large range of windows in the market in terms of thermal transmittance and solar factor for the glazing and frame solutions in different European climates through environmental and cost life cycle assessments and identifying their key drivers.

1.2. Objectives and research questions

The main goal of this PhD thesis is to analyze both full and streamlined LCA approaches to support the selection of windows to improve the life cycle environmental and economic sustainability of buildings. Firstly, an integrated cost and environmental full LCA approach combined with thermal dynamic simulation have been implemented for 32 alternative window solutions. The 32 alternative windows combine four framing materials (aluminum, PVC, fiberglass, and wood) and eight glazing alternatives (low versus high values for thermal transmittance and solar factors). All the components of the two main parts of the window system (frame and glass) have been characterized to identify those that contribute most to the total life cycle impacts, as well as their contribution to the embodied and operational impacts. Four cardinal orientations and three alternative European climates (Coimbra, Berlin, and Larnaca) have been assessed to explore how climate data and orientation influence the economic and environmental performance of the window solutions. Operational energy (covering heating and cooling), life cycle environmental impacts and costs have been assessed, and trade-offs identified using a bi-objective optimization (costs vs. environmental impacts). A sensitivity analysis has been performed to identify and rank the parameters that contribute the most to the variability in cost and environmental performance of windows for three European climates, as well as aiming to support the development of a streamlined LCA approach. A large number of window solutions have been comprehensively assessed, combining several window-related parameters (i.e. thermal transmittance value, solar factor, window-to-wall ratio, orientation), as well as operation-related parameters (i.e. number of occupants and ventilation rate). Even though the full LCA is a useful tool for assessing the environmental and cost performance, it is time-consuming and resource-intensive. To tackle this issue, an approach has been developed to streamline the environmental and cost LCA of windows incorporating probabilistic triage to support early-decision making for the selection of windows. This approach enables estimation of the economic and environmental performance of window solutions with different levels of information specified. In addition, this approach may reduce the uncertainty in the estimated results by means of sequentially specifying attributes based on a quantified attribute ranking. The consistency of the results by the streamlined approach has been verified with the full LCA results, aiming to show that it is not essential to perform a time-consuming and resource-intensive full LCA to select the most appropriate window solutions in terms of environmental and cost performances.

Table 1.1 presents the research questions based on the existing gaps, as well as the objectives and tasks defined in this PhD thesis to respond to the research questions.

Table 1.1 Research questions and specific objectives according to each chapter

Research question	Specific objectives/tasks	Chapter
1. What is the contribution of individual components of the framing and glazing options to the total embodied impacts of a window solution?	i. Assess the embodied environmental impacts of a standard size window (1.23 m × 1.48 m) with alternative framing materials (aluminum, fiberglass, PVC, and wood), and glazing solutions (low versus high values for thermal transmittance and solar factors), ii. Identify how the individual components of the two main parts of the window system (frame and glass) contribute to the total embodied impacts, iii. Identify the set of window solutions located in the Pareto optimal frontiers derived for the thermal transmittance versus embodied environmental impacts.	2
2. What are the trade-offs between embodied and operational environmental impacts of window solutions?	i. Assess embodied and operational impact trade-offs for the alternative window solutions.	3
3. How to select optimal windows that minimize energy consumption, costs, and environmental impacts throughout the life cycle of windows?	i. Perform an integrated cost and environmental life cycle assessment of alternative window solutions. ii. Identify trade-offs for the environmental impacts and costs of window solutions using a bi-objective optimization (costs vs. environmental impacts).	3
4. What are the key drivers and ranking parameters that contribute the most to the variability in cost and environmental performance of windows, considering various European climates?	i. Implement a comprehensive sensitivity analysis for a large number of window solutions combining several window-related parameters (i.e. thermal transmittance value, solar factor, window-to-wall ratio, orientation), as well as operation-related parameters (i.e. number of occupants and ventilation rate). ii. Find out key drivers and rank parameters that contribute the most to the variability in cost and environmental performance of windows, considering various climate regions in Europe.	4
5. Can a streamlined environmental and cost LCA approach support the selection of windows in the early-design stages of office buildings?	i. Integrate a streamlined embodied LCA, statistically-based operational energy and cost models for windows. ii. Assess the cost and environmental performance of window solutions with different levels of information specified. iii. Reduce the uncertainty in the estimated results by means of sequentially specifying attributes based on a quantified attribute ranking. iv. Investigate the consistency of the results presented by this probabilistic approach with the full LCA results.	5

1.3. Thesis main publications

This PhD thesis is based on the following key articles that are published or submitted to Web of Science journals. Abstracts and keywords for the articles are presented in Appendix I.

1. **Saadatian, S.**, Freire, F., Simões, N. (2021). “Embodied impacts of window systems: a comparative assessment of framing and glazing alternatives”, Journal of Building Engineering, vol. 35, Article 102042. https://doi.org/10.1016/j.jobe.2020.102042.

2. **Saadatian, S.**, Simões, N., Freire, F. (2021). “Integrated environmental, energy and cost life-cycle analysis of windows: Optimal selection of components”, Building and Environment, vol. 188, Article 107516. https://doi.org/10.1016/j.buildenv.2020.107516.

3. **Saadatian, S.**, Rodrigues, C., Freire, F., & Simões, N. (2022). “Key drivers of life-cycle environmental and cost assessment of windows for different European climate zones”, Journal of Building Engineering, vol. 50, 104206. https://doi.org/10.1016/j.jobe.2022.104206

4. **Saadatian, S.**, Rodrigues, C., Freire, F., Simões, N. (2021). “Environmental and cost life-cycle approach to support selection of windows in early stages of building design”, submitted to Journal of Cleaner Production (Under Review)

1.4. Thesis outline

This thesis consists of six chapters and is structured as presented in Figure 1.1, including this chapter with the introduction. A brief description of the remaining chapters, is presented in the next paragraphs.

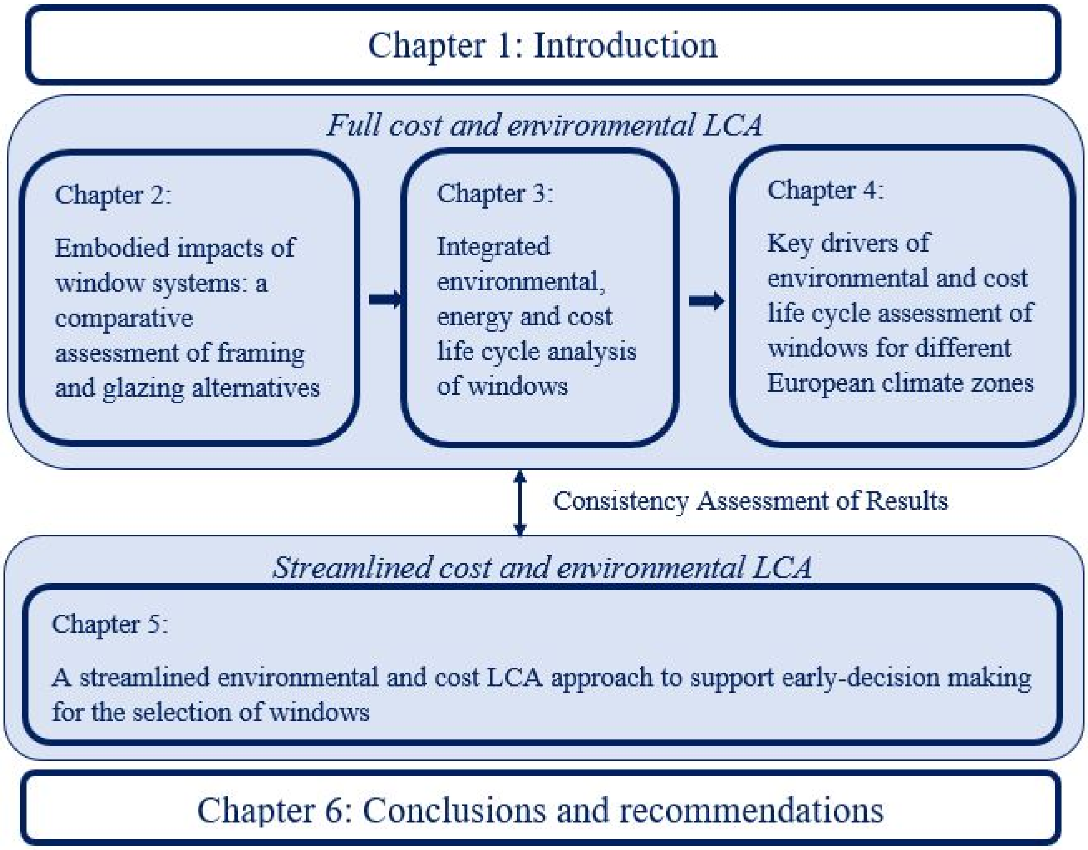


Figure 1.1 Thesis overview

Chapter 2 presents an assessment of the embodied environmental impacts of a standard size window (1.23 m × 1.48 m). It compares alternative framing materials (aluminum, fiberglass, PVC, and wood), and glazing solutions with different optical and thermal properties, so as to identify environmentally preferable (Pareto optimal) solutions. All the components of the two main parts of the window system (frame and glass) have been characterized to identify those that contribute most to the total embodied impacts. Finally, Pareto optimal frontiers have been presented for the thermal transmittance versus environmental impacts, for five categories.

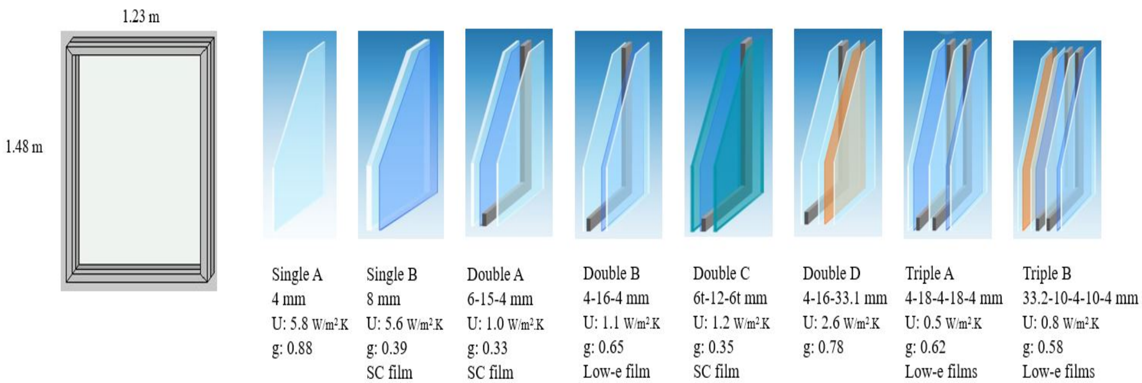
Chapter 3 presents an integrated cost and environmental LCA of window solutions combining alternative glazing and framing options for office use. Pareto optimal window solutions have been selected using a bi-objective optimization (costs vs. environmental impacts), considering various orientations and three different European climate regions. The influence of each window component (glazing and framing), as well as window properties (U- and g-value) on the overall environmental and cost life cycle assessment has been investigated. Furthermore, the simulation results have been validated in this chapter with respect to CEN Standard (CEN, 2007a) and the studied reference room model has been verified through application to a reference office building.

Chapter 4 applies a sensitivity analysis to identify the key drivers and rank the parameters that contribute the most to the variability in cost and environmental performance of windows, considering various climate regions in Europe, to support the selection of windows in an early-design stage of buildings. Sensitivity analysis can be a useful tool to realize the relationship between model inputs and outputs and quantify the difference between cost and environmental life cycle performance of different window configurations. A large number of window solutions have been comprehensively assessed, combining several window-related parameters (i.e. thermal transmittance value, solar factor, window-to-wall ratio, orientation), as well as operation-related parameters (i.e. number of occupants and ventilation rate).

Chapter 5 presents a streamlined environmental and cost LCA approach to support the selection of windows in the early-design stages of buildings based on the methodology developed by Hester et al. (2018) and Rodrigues et al. (2018). This probabilistic approach aims to assess the cost and environmental performance of window solutions with different levels of information specified, as well as reduce the uncertainty in the estimated results by means of sequentially specifying attributes based on a quantified attribute ranking. In addition, this chapter investigates the consistency of the results presented by this approach with full LCA results (presented in Chapters 2 and 3, as an LCA performed at late-design stages of building design) using a reference office room located in Portugal.

Chapter 6 draws the conclusions together by summarizing the key findings and contributions and providing recommendations for further research.

2. Embodied impacts of window systems: a comparative assessment of framing and glazing alternatives[1]



Abstract: This chapter presents an assessment of the embodied environmental impacts of a standard size window. It compares alternative frame materials (aluminum, fiberglass, polyvinyl chloride, wood) and glazing solutions with a view to identifying environmentally preferable (Pareto optimal) solutions. Environmental impacts were calculated for non-renewable primary energy, global warming, acidification, eutrophication, and ozone layer depletion. Pareto optimal frontiers were identified, showing the trade-offs between environmental impacts and thermal transmittance (U-value). All the components of the two main parts of a window (frame and glass) have been characterized to identify those that contribute most to the total embodied impacts.

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[1] Based on: Saadatian, S., Freire, F., Simões, N. (2021). "Embodied impacts of window systems: a comparative assessment of framing and glazing alternatives", Journal of Building Engineering, vol. 35, Article 102042. https://doi.org/10.1016/j.jobe.2020.102042 (Saadatian et al., 2021a)

2.1. Introduction

The embodied impacts of building materials can be considered as hidden impacts, away from the construction site and not visible to the user, but they are increasingly significant as buildings become more energy efficient (Finnegan et al., 2018; Seo et al., 2018). Embodied impacts of building materials are the sum of impacts (energy, environmental) required in the production and transportation, from raw material extraction to the building site, i.e. from 'cradle-to-site' (Tavares et al., 2019). Research and policy strategies have been focusing on reducing a building's operational energy (Kirankumar et al., 2020; Malmqvist et al., 2018), while the embodied impacts of building materials have been overlooked. Basbagill et al. (2013) highlighted the importance of addressing the embodied impacts of the building materials when improving energy efficiency of buildings. A reduction of operational impacts is normally associated with a rise in the contribution of embodied impacts related to building materials (Rodrigues and Freire, 2017).

Windows are essential building components that provide a view of the outside, admit daylight, enable solar heat gain and air ventilation (Baldinelli et al., 2014; Cuce and Riffat, 2015), but they need to provide noise insulation, resistance to wind loads (Shetty et al., 2014) and fire resistance (Wang et al., 2017). However, nowadays the selection of windows is highly dependent on its thermal behavior and most studies assessing the impacts of windows have been focused on operation (heating and cooling needs), ignoring embodied impacts.

Decision about the type of window frame, number of pane of glasses (single, double or triple), the gas filling the cavity (e.g., air or argon), coatings (e.g., low emissivity or solar control) will influence embodied impacts. The studies that assessed the embodied impacts of windows have mainly addressing individual components of windows. The majority have focused on frames (Carlisle and Friedlander, 2016; Seo et al., 2015; Sinha and Kutnar, 2012), while a few have analyzed glazing (Babaizadeh and Hassan, 2013; Syrrakou et al., 2005). For example, Sinha and Kutnar (2012) assessed three framing materials (aluminum, PVC, wood) and showed that the carbon footprint for aluminum and PVC frames was respectively 4 and 2 times higher than for a wood frame. For the PVC framing system, polyvinyl chloride contributed 45% to the embodied carbon, with stainless steel contributing 25%. Regarding the aluminum framing, the main contributions to the embodied carbon were aluminum (70%) and fiberglass reinforced plastic (10%). Seo et al. (2015) also analyzed the embodied impacts of an aluminum framing solution and found that aluminum is the main contributor to the embodied carbon (87%) of a window, due to the energy used in the smelting process. For glazing solutions, Syrrakou et al. (2005) assessed the environmental impacts associated with the production of electrochromic (EC) glazing compared with various insulating glass units. The results showed that EC glazing could have lower environmental embodied impacts, plus lower cost, and better thermal and optical behavior.

From the literature review, we have concluded that are few studies addressing the embodied impacts of individual components of windows (glazing and framing and their constituents) and it is essential to break each individual window part down into its components to determine the key contributors to the total embodied impacts. In addition, there have been no comparative studies on the embodied impact assessment of windows which investigate the influence of thermal transmittance and solar factors, together with the effect of individual constituents of glazing and framing options on the total embodied impacts of a window solution. The enhancement of window designs has been mainly focused on mechanical, architectural, thermal, and acoustical aspects; however, environmental impacts are increasingly important and embodied impacts have not been thoroughly assessed.

This chapter proposes an approach based on embodied impact assessment and Pareto optimal frontier to support environmentally friendly design of windows. A comprehensive assessment of the embodied environmental impacts of a standard size window (1.23 m × 1.48 m) was implemented for 32 window systems (based on four framing materials and eight glazing solutions), which are compared with a view to identifying environmentally preferable (Pareto optimal) solutions. A “cradle-to-site” analysis has been performed to calculate the embodied impacts, including raw material extraction and transport, manufacture of materials and components, as well as transport to the building site. Alternative framing materials with different thermal transmittances (aluminum, fiberglass, PVC, and wood), and glazing solutions (for single, double, tripled-glazed, from low to high values of thermal transmittance and solar factors) have been assessed to identify those that contribute most to the total embodied impacts. The combination of the selected glazing and framing alternatives gives a range of thermal transmittance of the whole window between 0.74 and 5.84 W/(m^{2}K). Finally, we present the Pareto optimal frontiers derived for the thermal transmittance versus environmental impacts, for five categories.

This chapter has four sections, including this introduction. Section 2 presents the materials and methods. Section 3 analyzes and discusses the main results. These relate to how the individual components contribute to the total embodied impacts for the different framing and glazing solutions, as well as the set of window solutions located in the Pareto optimal frontiers. Section 4 draws the conclusions.

2.2. Materials and methods

2.2.1. Glazing solutions

Many glazing solutions are used in the windows of buildings including ones that use different types of glass, numbers of panes of glass and kinds of glass film. Regarding strength, glass can be classified as annealed, tempered (or toughened) and laminated. Annealed glass is the basic form of the product after the annealing process on the float glass, which allows the melted glass to cool gently to relieve any residual internal stresses in the glass. Tempered glass is four to five times stronger than annealed glass. This glass type is made by heating the annealed glass in a tempering furnace to approximately 650°C and then cooling it rapidly. Tempered glass is more resistant to breakage and there is less risk of injury or damage in the event of breaking because of shattering in small pieces. Laminated glass is made of two sheets of annealed or tempered glass together with Polyynyl Butyral (PVB) interlayer. Laminated glass provides more safety and security because, if it breaks, the broken pieces are held together by an interlayer which prevents any person or object from entering. There are different kinds of glass films according to the function that is required of them. Solar control films, for example, originally reduced solar heat gain and cooling energy needs in summer, but the same effect of reducing solar heat gain in winter increased heating energy needs. The other type is low-E film that not only plays the role of solar control film in summer but also prevents heat loss through windows in winter (Vengatesan, 2017). Figure 2.1 presents the most common glazing compositions changing the number of panes and type of glass, adapted from the technical catalogue of a glass manufacturer (Viracon Glass Fabrication, 2014).

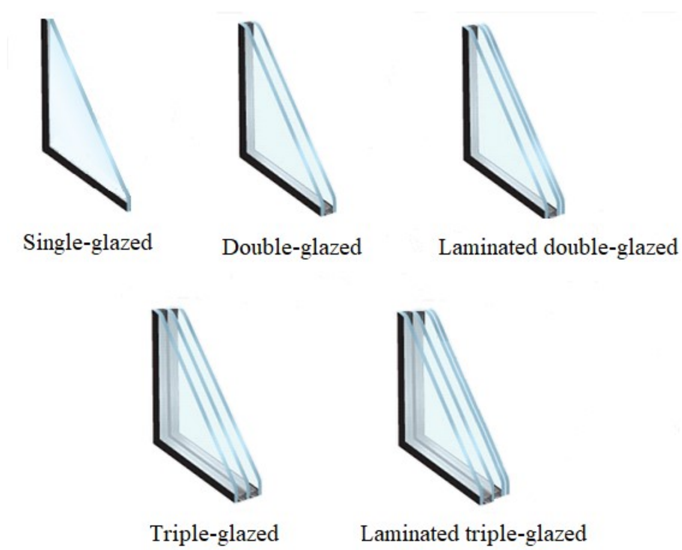


Figure 2.1 Glazing compositions changing the number of panes and type of glass, adapted from (Viracon Glass Fabrication, 2014)

In terms of the number of glass panes, there are three kinds of glazing systems, namely, single, double, and triple-glazed systems. A single-glazing solution is made of a single pane of glass (thickness ranges typically from 3 mm to 12 mm). Double- and triple-glazing solutions consist of two and three glass panes separated by an aluminum or plastic spacer and a gas filling (generally, air or argon) to improve the thermal efficiency. The spacer is bonded to the glass panes with a sealant and filled with a desiccant (typically a zeolite) to remove any moisture inside the cavity (Vengatesan, 2017). Figure 2.2 presents a schematic design of a single-, double- and triple-glazing system, together with their components.

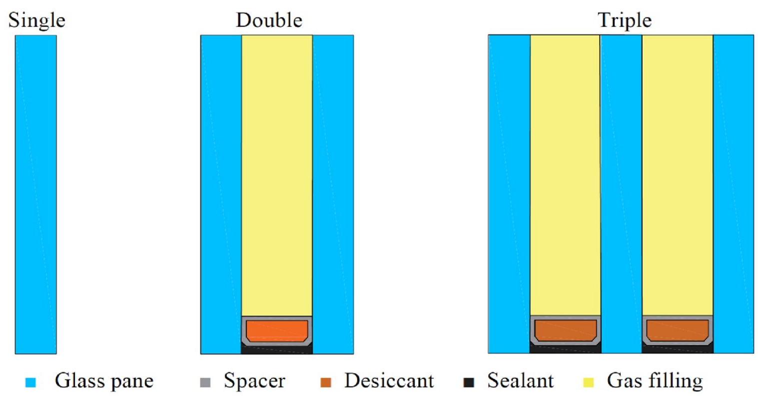


Figure 2.2 Schematic design of single-, double- and triple-glazing solutions

Alternative glazing solutions were selected based on typical low and high values of thermal transmittance (U-value) and solar factor (g-value) within the commercially available range for the three glazing types. Next, the type of glass (annealed, tempered and laminated) and films (solar control or low-e) for the solutions were chosen based on the Saint Gobain Glass library (Saint-Gobain Glass, 2019), a leading manufacturer of flat glass for the European market. Glazing solutions were defined using Berkeley Lab Window 7.4 software (Lawrence Berkeley National Laboratory, 2019), considering various glass types and films. Table 2.1 lists the alternative glazing solutions characterized by their optical and thermal properties. Cavities between panes of glass are filled with 100% Argon gas.

Table 2.1 Alternative glazing solutions characterized by thermal and optical properties

Glazing solution ID	Glass layers	Glass type	U-value ($W/(m^2K)$)	g-value	Total thickness in mm (G_1-C_1-G_2-C_2-G_3) [1]	Laminated form ($G_1G_2.N_L$) [2]	Coating type (face no. with coating) [3]	Coating material
Single A (SA)	Single	Annealed (A)	5.8	0.88	4.0 (4A)	-	-	-
Single B (SB)	Single	Annealed (A)	5.6	0.39	8.0 (8A)	-	Solar control (2)	Sodium fluorosilicate
Double A (DA)	Double	Annealed (A)	1.0	0.33	25.0 (6A-15-4A)	-	Solar control (2)	Sodium fluorosilicate
Double B (DB)	Double	Annealed (A)	1.1	0.65	24.0 (4A-16-4A)	-	Low-E (3)	Copper oxide
Double C (DC)	Double	Tempered (T)	1.2	0.35	25.0 (6T-12-6T)	-	Solar control (2)	Sodium fluorosilicate
Double D (DD)	Double	Laminated (L)	2.6	0.78	26.4 (4A-16-6.4L)	3A3A.1	-	-
Triple A (TA)	Triple	Annealed (A)	0.5	0.62	48.0 (4A-18-4A-18-4A)	-	Low-E (2&5)	Copper oxide
Triple B (TB)	Triple	Laminated (L)	0.8	0.58	34.8 (6.8L-10-4A-10-4A)	3A3A.2	Low-E (2&5)	Copper oxide

[1] G_1: 1st glass pane thickness & type, C_1: 1st cavity thickness, G_2: 2nd glass pane thickness & type, C_2: 2nd cavity thickness, G_3: 3rd glass pane thickness & type.
[2] G_1: 1st glass pane thickness & type, G_2: 2nd glass pane thickness & type, N_L: number of laminated layers.
[3] Glass faces are identified by number, starting with the exterior surface.

Table 2.2 lists the relevant data sources of the components of the selected glazing solutions.

Table 2.2 Data sources for glazing solutions components

Glazing solution components	Data source
Annealed glass	SAINT-GOBAIN - EPD verified - PLANICLEAR® (Registration number: S-P-00882) (Saint-Gobain Glass, 2019)
Solar control film on single glazing	SAINT-GOBAIN - EPD verified - coated glass on SGG PLANICLEAR® & SGG DIAMANT® (Registration number: S-P 00926) (Saint-Gobain Glass, 2019)
Solar control film on double glazing	SAINT-GOBAIN - EPD verified – Double Glazing CLIMAPLUS® / CLIMALIT® PLUS (Registration number: S-P-00932) (Saint-Gobain Glass, 2019)
Low-e film on double glazing	SAINT-GOBAIN - EPD verified – Double Glazing CLIMAPLUS® / CLIMALIT® PLUS (Registration number: S-P-00932) (Saint-Gobain Glass, 2019)
Tempered glass	SAINT-GOBAIN - EPD verified – Double Glazing CLIMAPLUS® / CLIMALIT® PLUS (Registration number: S-P-00932) (Saint-Gobain Glass, 2019)
Laminated glass	SAINT-GOBAIN - EPD verified – Double Glazing CLIMALIT® (Registration number: S-P-00934) (Saint-Gobain Glass, 2019)
Low-e film on triple glazing	SAINT-GOBAIN - EPD verified – Triple Glazing CLIMATOP (Registration number: S-P 00933) (Saint-Gobain Glass, 2019)
Sealant	Polysulphide, sealing compound (Hischier and Gallen, 2007)
Spacer	Aluminium, production mix, at plant (Classen et al., 2009)
Desiccant	Zeolite, powder, at plant (Hischier and Gallen, 2007)
PVB interlayer	SAINT-GOBAIN - EPD verified – Double Glazing CLIMALIT® (Registration number: S-P-00934) (Saint-Gobain Glass, 2019)
Argon gas	SAINT-GOBAIN - EPD verified – Double Glazing CLIMAPLUS® / CLIMALIT® PLUS (Registration number: S-P-00932) (Saint-Gobain Glass, 2019)

2.2.2. Framing options

The most used frame materials are PVC, wood, and aluminum. Figure 2.3 shows representative cross-section for each of these options.

Figure 2.3 Cross-section images for PVC, wood, and aluminum frame options

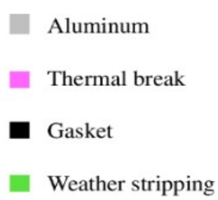
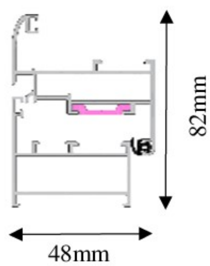
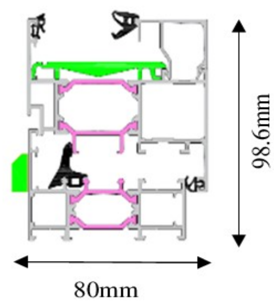
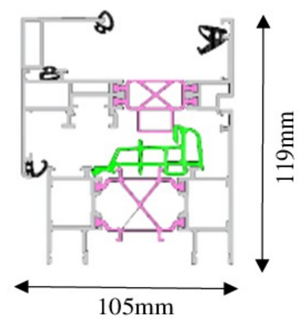
PVC frames are reinforced with stainless steel inside, while in the case of aluminum, a low thermal conductivity element (thermal break) is fitted into the frame to reduce conductive energy losses. The thermal break is a low thermal conductivity material placed between internal and external metal parts of aluminum frame to prevent conductive thermal bridges. Fiberglass frame is also considered in this study as a solution that is growing in the market. Table 2.3 lists the components of the selected four frame materials (aluminum, PVC, fiberglass, and wood), and the relevant data sources.

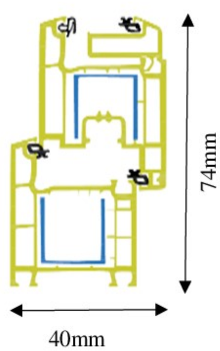
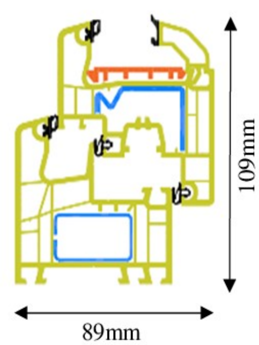
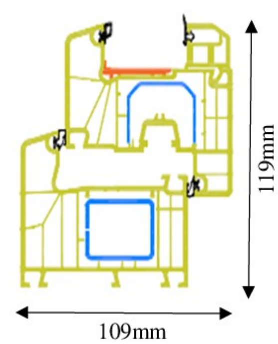
Table 2.3 Frame material components

Frame Components	Data source
Aluminum (ALU)	
-Aluminum	-Aluminum, produced at plant, mix of primary and secondary ALU with 32% share of secondary aluminum (Classen et al., 2009)
-Thermal break	-Fiberglass reinforced plastic, polyamide with a fiber content of 30% which is injected (Kellenberger et al., 2007)
-Gasket	-Synthetic rubber, produced at plant (Hischier and Gallen, 2007)
-Weather stripping	-Silicone foam, copolymer, produced at plant (Hischier and Gallen, 2007)
Polyvinyl chloride (PVC)	
-PVC	-Polyvinyl chloride, produced at plant (Kellenberger et al., 2007)
-Stainless steel	-Steel, low-alloy, produced at plant, containing less than 5% alloying elements in total (Classen et al., 2009)
-Gasket	-Synthetic rubber, produced at plant (Hischier and Gallen, 2007)
-Bonding inside	-Polystyrene foam, produced at plant (Hischier and Gallen, 2007)
Fiberglass (FGL)	
-Fiberglass	-Fiberglass, produced at plant (Kellenberger et al., 2007)
-Adhesive tape	-Polyethylene, produced at plant (Hischier and Gallen, 2007)
-Gasket	-Synthetic rubber, produced at plant (Hischier and Gallen, 2007)
-PVC part	-Polyvinyl chloride, produced at plant (Kellenberger et al., 2007)
Wood (WOO)	
-Softwood	-Sawn timber, softwood, produced at plant, carbon dioxide uptake is based on the carbon content of wood (49.4% of dry wood matter) (Werner et al., 2007)
-Gasket	-Synthetic rubber, produced at plant (Hischier and Gallen, 2007)

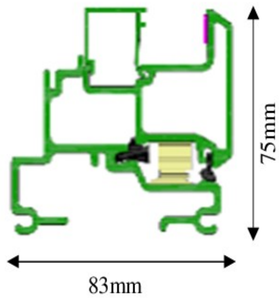
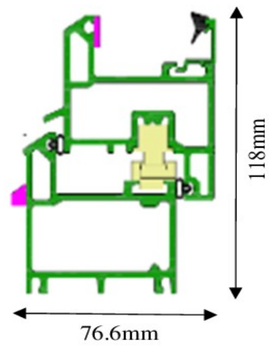
Each frame material is categorized into different frame types according to the characteristics of the applied glazing solution, such as number of panes and total thickness. Table 2.4 presents the selected framing options together with thermal transmittance values and the schematic designs. The schematic designs are representatives of solutions provided by different suppliers.

Table 2.4 Selected framing options

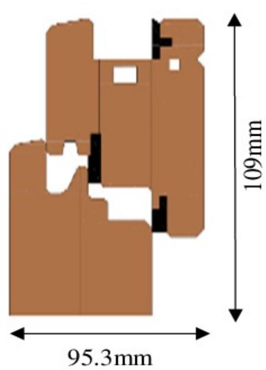
a) Aluminum Frame			
Solution ID	ALU.S [1]	ALU.D	ALU.T
Legend: 			
Frame U-value (W/(m^{2}K))	5.97	2.00	1.50

b) Polyvinyl chloride (PVC)			
Solution ID	PVC.S	PVC.D	PVC.T
Legend: 			
Frame U-value (W/(m^{2}K))	1.60	1.20	1.00

c) Fiberglass (FGL)		
Solution ID	FGL.SD	FGL.DT

Legend: 		
Frame U-value (W/(m²K))	1.78	1.07

d) **Wood (WOO)**

Solution ID	WOO.SDT
Legend: 	
Frame U-value (W/(m²K))	1.52

[1] S stands for single, D for double and T for triple-glazing.
Note: The schematic design of framing solutions is a not-to-scale drawing.

Table 2.5 lists the bill of materials for standard size window systems measuring 1.23 m × 1.48 m (International Organization for Standardization, 2017a) considering the full set of framing and glazing options. Thirty-two window systems are presented, consisting of four frame materials (listed in Table 2.4) and eight glazing solutions (listed in Table 2.5). Technical data were gathered from frame producers and suppliers and from environmental product declarations (EPDs) for glazing (Saint-Gobain Glass, 2019) to examine the properties and quantities of materials required for each window solution (foreground data). The U-values of the window solutions presented in Table 2.5 were calculated in accordance with ISO 10077-2 (2017).

Table 2.5 Inventory of window systems with alternative glazing and framing materials: a) aluminum frame; b) PVC frame; c) fiberglass frame; d) wood frame.

a) aluminum frame

Window system ID[1]	U-value (W/(m^{2}K))	Mass of framing and glazing components (kg/1.82m^2 of window area)										
		Annealed glass	Tempered glass	Sealant	Space bar	Desiccant	Argon	PVB interlayer	Aluminum	Thermal break	Gasket	Weather stripping
ALU.S_SA	5.84	15.19	-	-	-	-	-	-	7.30	0.30	0.15	-
ALU.S_SB	5.74	30.38	-	-	-	-	-	-	7.69	0.30	0.15	-
ALU.D_DA[2]	1.39	34.35	-	0.26	0.34	0.23	0.03	-	14.96	4.03	1.47	2.18
ALU.D_DB	1.46	27.48	-	0.29	0.37	0.26	0.03	-	14.97	4.03	1.47	2.18
ALU.D_DC[2]	1.54	-	41.22	0.22	0.30	0.19	0.03	-	14.96	4.03	1.47	2.18
ALU.D_DD	2.56	34.35	-	0.29	0.37	0.26	0.03	0.10	14.93	4.03	1.47	2.18
ALU.T_TA	0.87	42.36	-	0.86	0.95	0.83	0.08	-	15.75	2.16	2.64	1.45
ALU.T_TB	1.10	49.42	-	0.48	0.56	0.45	0.04	0.47	16.06	2.16	2.64	1.45

b) PVC frame

Window system ID*	U-value (W/(m^{2}K))	Mass of framing and glazing components (kg/1.82m^2 of window area)										
		Annealed glass	Tempered glass	Sealant	Space bar	Desiccant	Argon	PVB interlayer	PVC	Stainless steel	Gasket	Bonding inside
PVC.S_SA	4.92	14.61	-	-	-	-	-	-	18.99	16.37	0.66	-
PVC.S_SB	4.82	29.22	-	-	-	-	-	-	18.86	16.37	0.66	0.34
PVC.D_DA[2]	1.16	33.65	-	0.26	0.34	0.23	0.03	-	13.12	11.00	0.81	1.06
PVC.D_DB	1.23	26.92	-	0.28	0.36	0.26	0.03	-	13.14	11.00	0.81	1.06
PVC.D_DC[2]	1.30	-	40.38	0.22	0.30	0.19	0.03	-	13.12	11.00	0.81	1.06
PVC.D_DD	2.31	33.65	-	0.28	0.36	0.26	0.03	0.09	13.08	11.00	0.81	1.06
PVC.T_TA	0.74	39.00	-	0.79	0.87	0.77	0.08	-	15.72	14.81	0.84	0.70
PVC.T_TB	0.96	45.50	-	0.44	0.52	0.42	0.04	0.43	15.17	13.36	0.65	0.70

c) fiberglass frame

Window system ID*	U-value (W/(m^{2}K))	Mass of framing and glazing components (kg/1.82m^2 of window area)										
		Annealed glass	Tempered glass	Sealant	Space bar	Desiccant	Argon	PVB interlayer	Fiberglass	Polyethylene adhesive tape	Gasket	PVC part
FGL.SD_SA	4.95	15.10	-	-	-	-	-	-	11.28	0.47	0.50	0.99
FGL.SD_SB	4.85	30.20	-	-	-	-	-	-	11.21	0.47	0.50	0.99
FGL.SD_DA[2]	1.24	37.75	-	0.29	0.38	0.26	0.03	-	10.93	0.47	0.50	0.99
FGL.SD_DB	1.33	30.20	-	0.32	0.41	0.29	0.03	-	10.96	0.47	0.50	0.99
FGL.SD_DC[2]	1.41	-	45.30	0.24	0.33	0.21	0.03	-	10.93	0.47	0.50	0.99
FGL.DT_DD	2.23	32.38	-	0.27	0.35	0.25	0.03	0.09	15.85	0.83	0.76	1.31
FGL.DT_TA	0.77	38.85	-	0.79	0.87	0.76	0.08	-	15.12	0.83	0.76	1.31
FGL.DT_TB	0.98	45.33	-	0.44	0.52	0.42	0.04	0.43	15.47	0.83	0.76	1.31

d) wood frame

Window system ID*	U-value (W/(m^{2}K))	Mass of framing and glazing components (kg/1.82m^2 of window area)								
		Annealed glass	Tempered glass	Sealant	Space bar	Desiccant	Argon	PVB interlayer	Softwood	Gasket
WOO.SDT_SA	4.52	13.46	-	-	-	-	-	-	16.16	1.24
WOO.SDT_SB	4.43	26.92	-	-	-	-	-	-	16.02	1.24
WOO.SDT_DA[2]	1.24	33.65	-	0.26	0.34	0.23	0.03	-	15.44	1.24
WOO.SDT_DB	1.31	26.92	-	0.28	0.36	0.26	0.03	-	15.48	1.24
WOO.SDT_DC[2]	1.39	-	40.38	0.22	0.30	0.19	0.03	-	15.44	1.24
WOO.SDT_DD	2.40	33.65	-	0.28	0.36	0.26	0.03	0.09	15.39	1.24
WOO.SDT_TA	0.87	40.38	-	0.82	0.90	0.80	0.08	-	14.64	1.24
WOO.SDT_TB	1.09	47.11	-	0.46	0.54	0.43	0.04	0.44	15.10	1.24

[1] Window system ID is expressed as frame ID_glazing ID.

[2] The frame type selected for DA and DC according to each material option, are similar due to their equally total thicknesses.

Note: Glass films (solar control and low-E) are quantified by glass area because of their ultra-lightweight design.

2.2.3. Embodied impact assessment

To calculate the embodied impacts of a standard size window (1.23 m × 1.48 m), a 'cradle-to-site' model of the 32 alternative window systems was implemented to the following phases: raw material extraction, transport and manufacture of materials and components, as well as transport to the building site. The calculation had followed the life cycle assessment methodology (Bruijn et al., 2002; Pennington et al., 2004), focusing on the ´cradle-to-site' phases (Tavares et al., 2019). The main (foreground) data is the bill of materials (Table 2.5) presented in the previous section. Data for background processes (such as production of materials) were based on Althaus et al. (2007); Classen et al. (2009); Hischier and Gallen (2007); Kellenberger et al. (2007). Data for fuels for transportation was from Spielmann et al. (2007). Finishing materials were assumed to be locally transported, for an average 50 km distance (single trip in a 3.5-16t lorry) (Spielmann et al., 2007).

The 'cradle-to-site' model has been implemented in the SimaPro software (PRé Consultants, 2016). The embodied energy has been calculated for non-renewable primary energy (NRPE) using the method cumulative energy demand (CED) (Frischknecht et al., 2007). Four environmental impact categories have been calculated, namely global warming 100-year time horizon (GW in kg CO_2 eq.), acidification (AC in kg SO2 eq.), eutrophication (EU in kg PO4 eq.), and ozone layer depletion (OD in kg CFC-11 eq.), using the CML 2001 method. These impact categories are recommended by European standards EN 15804 (2012); EN 15978 (2011) and have been widely used in building life cycle studies (Monteiro et al., 2016; Rodrigues et al., 2018).

2.2.4. Interpretation of the results – Pareto optimal frontiers

The concept of the Pareto optimal frontier (a set of non-dominated, non-inferior or efficient solutions) introduces mathematical fundamentals for multi-objective problems. A solution is non-dominated when there is no other feasible solution that concurrently ameliorates all the objective function values. In other words, ameliorating one of the objectives involves worsening at least one of the other objective function values (Antunes et al., 2016).

The Pareto optimal frontier method was applied to bi-objective integer problems (U-value vs environmental impact, for each of the five impact categories). Pareto-optimal solutions are selected following the concept of dominance among vectors in the objective space (Sánchez et al., 2016). According to dominance concept, solution x_1 dominates solution x_2 if the objective function for x_1 ($f(x_1)$) is better than the objective function for x_2 ($f(x_2)$) and x_1 is not worse than x_2 in at least one objective (Kiewidt and Thöming, 2019). Therefore, x_1 is known as a non-dominated solution. In this study, the two objective functions to be minimized are the thermal transmittance and embodied impacts of window solutions. In Pareto optimality, the dominance concept will be employed for all solutions to result with a set of Pareto optimal solutions that are non-dominated in the entire objective space (Syed Mustaffa et al., 2019). The mathematical expression of this is shown in the following equation:

$x_1 \prec x_2$ (x_1 dominates x_2) if

$\forall i: f_i(x_1) \leq f_i(x_2) \wedge \exists j: f_j(x_1) < f_j(x_2)$

where, j = 1, 2, ..., n, which is the number of objective functions.

Pareto optimal solutions consist of supported and unsupported efficient solutions. Figure 2.4 illustrates the distinction between supported and unsupported nondominated solutions in a bi-objective problem, with both functions to be minimized. The x-axis shows the thermal transmittance (U-value) of window solutions $f_1(x_i)$ and the y-axis the embodied impact $f_2(x_i)$. Supported non-dominated solutions are x_1, x_2 and x_4, and unsupported non-dominated solution is x_3. The unsupported non-dominated solution (x_3) is dominated by some (infeasible) convex combinations of its two adjacent supported non-dominated solutions (x_2 and x_4). All convex combinations are defined by the intersection of the dominance cone stemming from x_3 with the segment connecting x_2 and x_4. Solution x_3 lies inside the convex hull defined by the supported solutions. The Pareto optimal frontier concept makes it possible to identify the set of non-dominated solutions for the window systems and show the trade-offs between the non-dominated solutions in terms of U-value and embodied impacts.

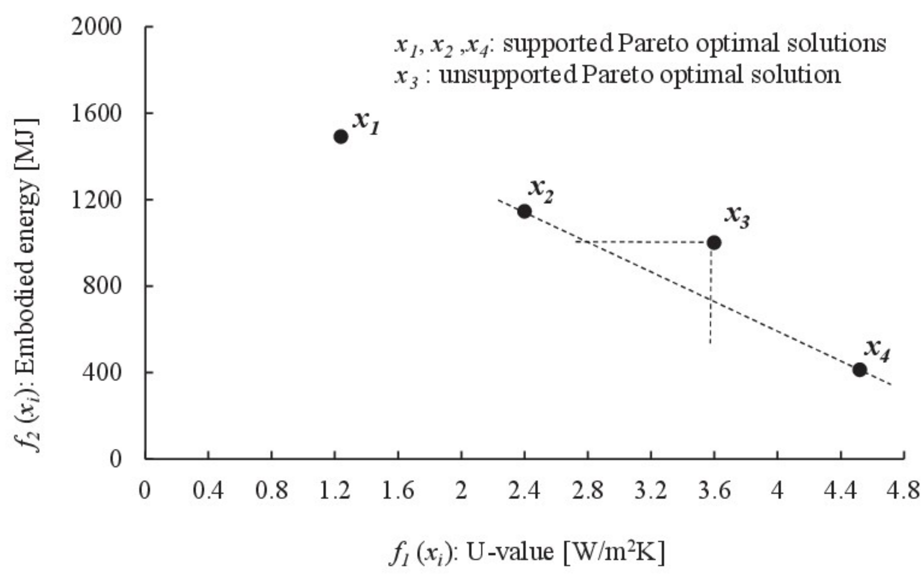


Figure 2.4 Pareto optimal frontier consisting of supported and unsupported non-dominated solutions

2.3. Results and discussion

The embodied impacts for the window systems consisting of alternative framing and glazing solutions are analyzed and discussed in this section. Subsection 2.3.1 compares the embodied impacts of the alternative glazing solutions and framing options. The subsection concludes by describing the embodied impacts of the alternative window systems to show the contribution of glazing and framing. In subsection 2.3.2, Pareto optimal frontiers are presented based on the multiple objectives (thermal transmittance vs. environmental impacts, for five categories) to identify optimal window solutions.

2.3.1. Embodied impact assessment – window systems with glazing and framing alternatives

2.3.1.1. Glazing alternatives

This subsection presents the contribution of individual components to the total embodied impacts of each glazing solution (from ‘cradle-to-site’), along with a comparative analysis of the embodied impacts of the eight glazing solutions, aiming to encourage the use of products with fewer environmental burdens.

Figure 2.5 shows the embodied impacts of the eight glazing solutions for the standard size and frameless window. Glass is the most significant glazing component as it accounts for more than 62% of the total embodied impacts of a glazing solution. Tempered glass is the largest contributor in Double C for all impact categories (about 95%) and is almost 1.5 times higher than the annealed glass because of the tempering process (Kua and Lu, 2016). For the laminated glazing solutions (in Double D & Triple B), the PVB interlayer accounts for 15% and 20% of total GW and NRPE embodied impacts, respectively. For eutrophication, glass coating (low-E) has significant impacts because of the electricity used in its production. The low-E film (copper oxide) contributes approximately 35% of the total embodied EU of the glazing system as copper provides the eutrophic conditions by depleting dissolved oxygen (Rathore et al., 2016). The contribution of Argon gas (<0.04%) and sealant (<2%) is not significant (all categories).

The impacts for the five categories assessed show similar pattern with increasing impacts associated with the increasing weight of glass in the solutions, with some exceptions, namely the laminated glazing (Double D and Triple B) and low-E coated glazing solutions (Double B, Triple A and Triple B). The magnitude of impacts is different for the laminated glazing solutions regarding non-renewable primary energy and global warming, and for the low-E coated solutions regarding eutrophication and ozone layer depletion.

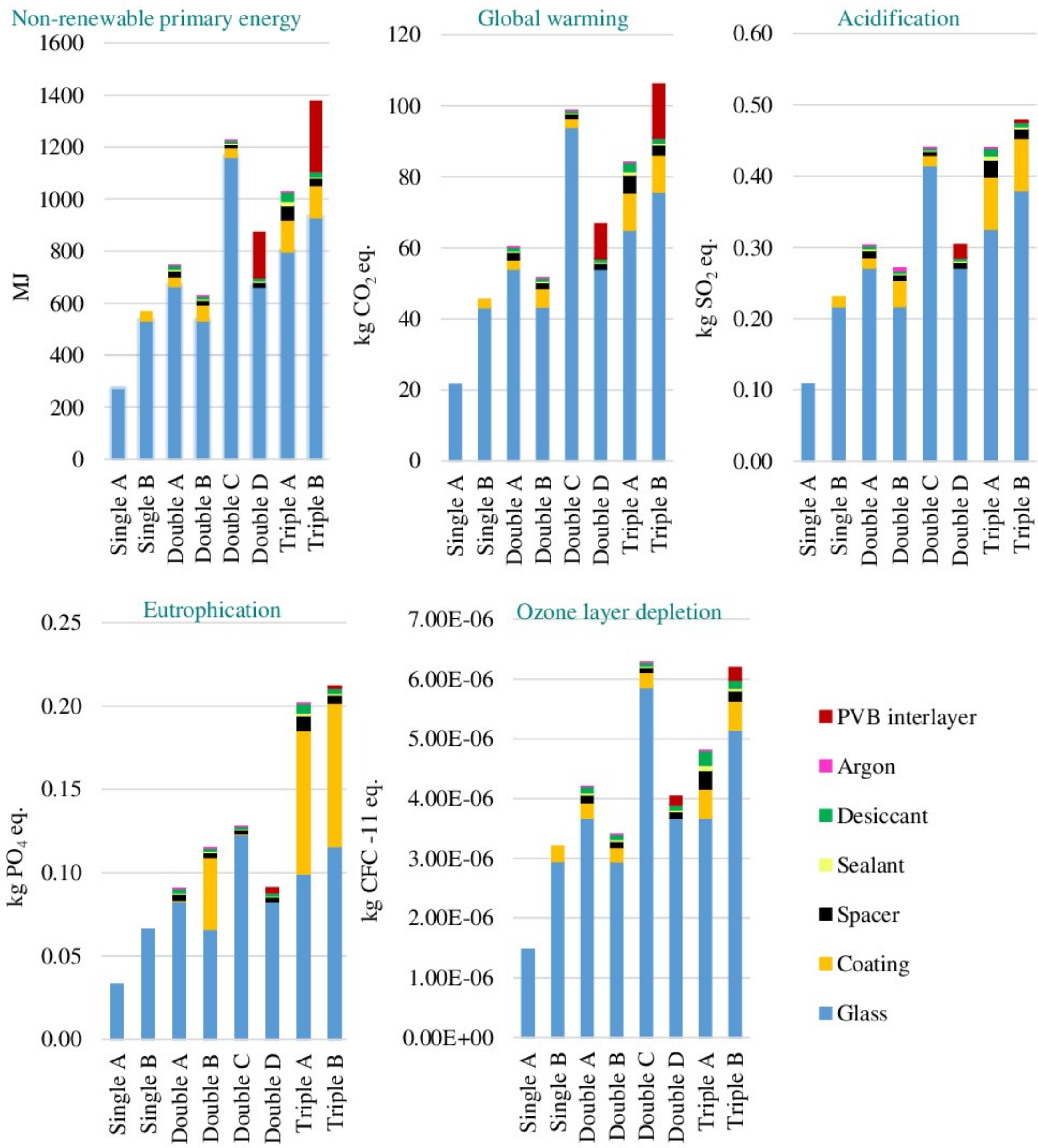


Figure 2.5 Embodied impact assessment of eight alternative glazing solutions, by component, for 1.82 m^2 frameless window

2.3.1.2. Framing alternatives

The embodied impacts of the individual frame materials (ALU, PVC, FGL and WOO) were evaluated per component and then compared with the other framing alternatives for each environmental impact category. Figure 2.6 presents the embodied impact assessment of the alternative framing for the standard size window. The results show that the wood frame is the option with the lowest embodied impacts among all categories. The aluminum frame for the double- and triple-glazed solutions (ALU.D & ALU.T) has the highest impacts in all categories. Regarding embodied energy, aluminum is the largest contributor in the ALU frame options (62-93%), followed by thermal break (10-23%), weather stripping (4-10%) and gasket (3-10%). PVC is the main contributor in the PVC frame solutions (60-66%), followed by stainless steel (24-29%), bonding inside (4-9%) and gasket (4-6%). Fiberglass in the FGL frame options has the highest share of embodied impacts (~74%), then nearly equal shares for the polyethylene adhesive tape, gaskets and PVC part (6-10%). The WOO frame option is made of wood and gaskets, with approximately equal contributions to the total embodied impacts. Stainless steel is the component with the highest embodied eutrophication impacts for the PVC frame solutions, due to the galvanizing process (coating steel with zinc). For the ALU frame options, the thermal break contribution is nearly one-fourth of aluminum to terrestrial acidification and eutrophication and almost 20% for the other categories. These results provide a useful indication on the influence of each frame component on the embodied impacts of the different framing material options.

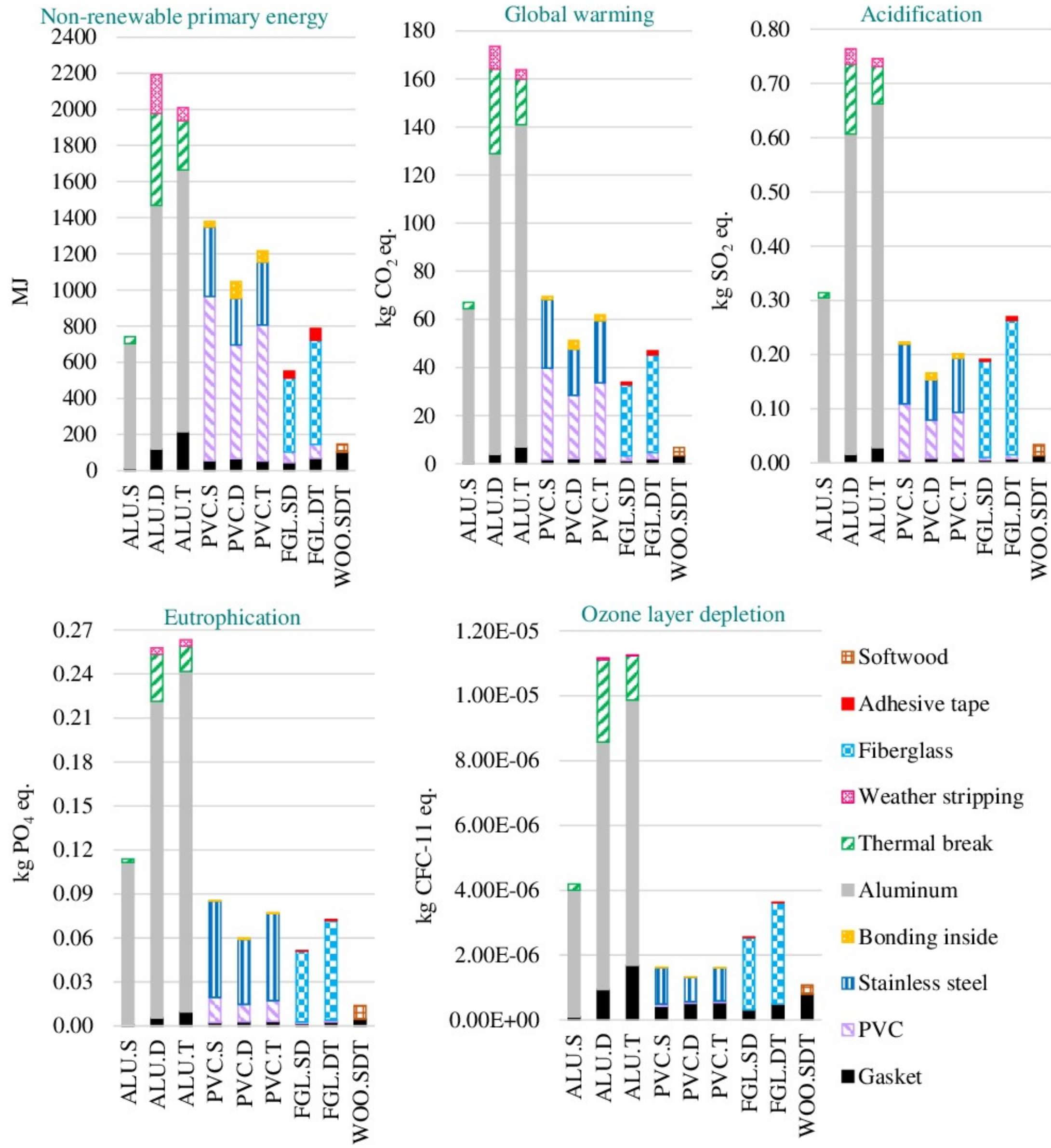


Figure 2.6 Embodied impact assessment of four frame material options per component, for a standard size window

2.3.1.3. Alternative window systems

Figure 2.7 presents the embodied impacts of the different window systems, for help understand the contribution of the individual glazing and framing solutions in each window system. The window systems and their thermal and optical properties are listed above, in Table 2.5. Figure 2.7 shows the magnitude of embodied impacts of both the glazing and framing solutions.

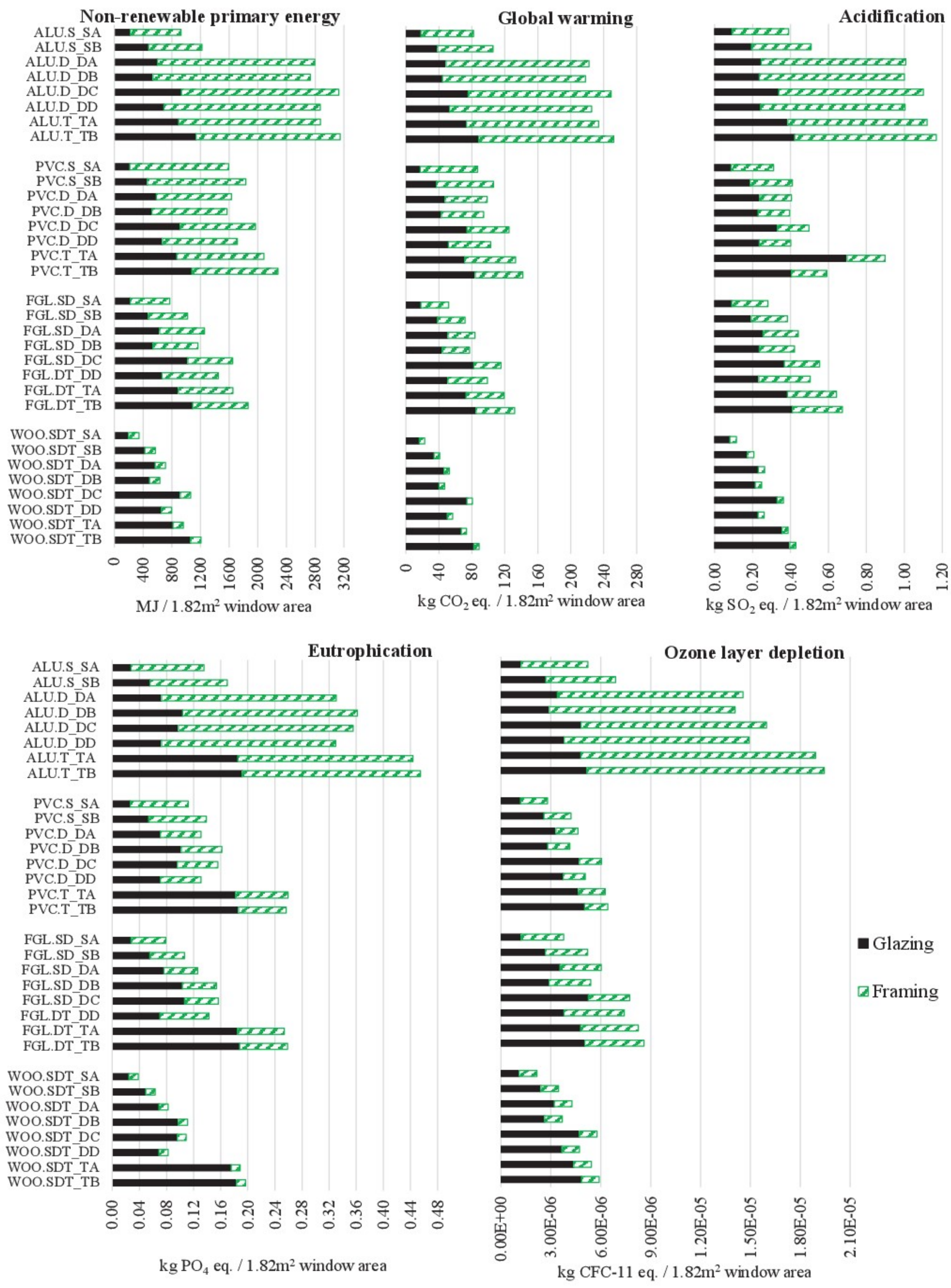


Figure 2.7 Embodied impacts - breakdown of alternative window systems by glazing and framing solutions

For the aluminum frame window systems, the framing solution represents 60-80% of total embodied impacts. For the PVC and FGL frame window systems, the framing can have a low or high share of the total embodied impacts, depending on the selected glazing solution. The type of glazing influences the contribution; for the single-glazed options the highest embodied impact contribution comes from the framing (58-86%), a nearly similar contribution is found for double-glazed solutions and a smaller contribution with triple-glazed options (22-40%). The evaluation of these three examples shows that the glazing type has a significant influence on the embodied impacts share that needs to be considered. For wood frame solutions, the contribution of the framing (<30%) is much less significant (all categories).

2.3.2. Pareto optimal frontiers for the alternative window solutions

Figure 2.8 shows the embodied impacts (discussed in the previous section) versus U-value for all window solutions, for each of the five impact categories. The x-axis shows the thermal transmittance values of window solutions and the y-axis the embodied impacts within the five environmental impact categories (NRPE, GW, AC, EU and OD). Figure 2.8 shows that most of the alternative window systems are dominated by a small number of window solutions.

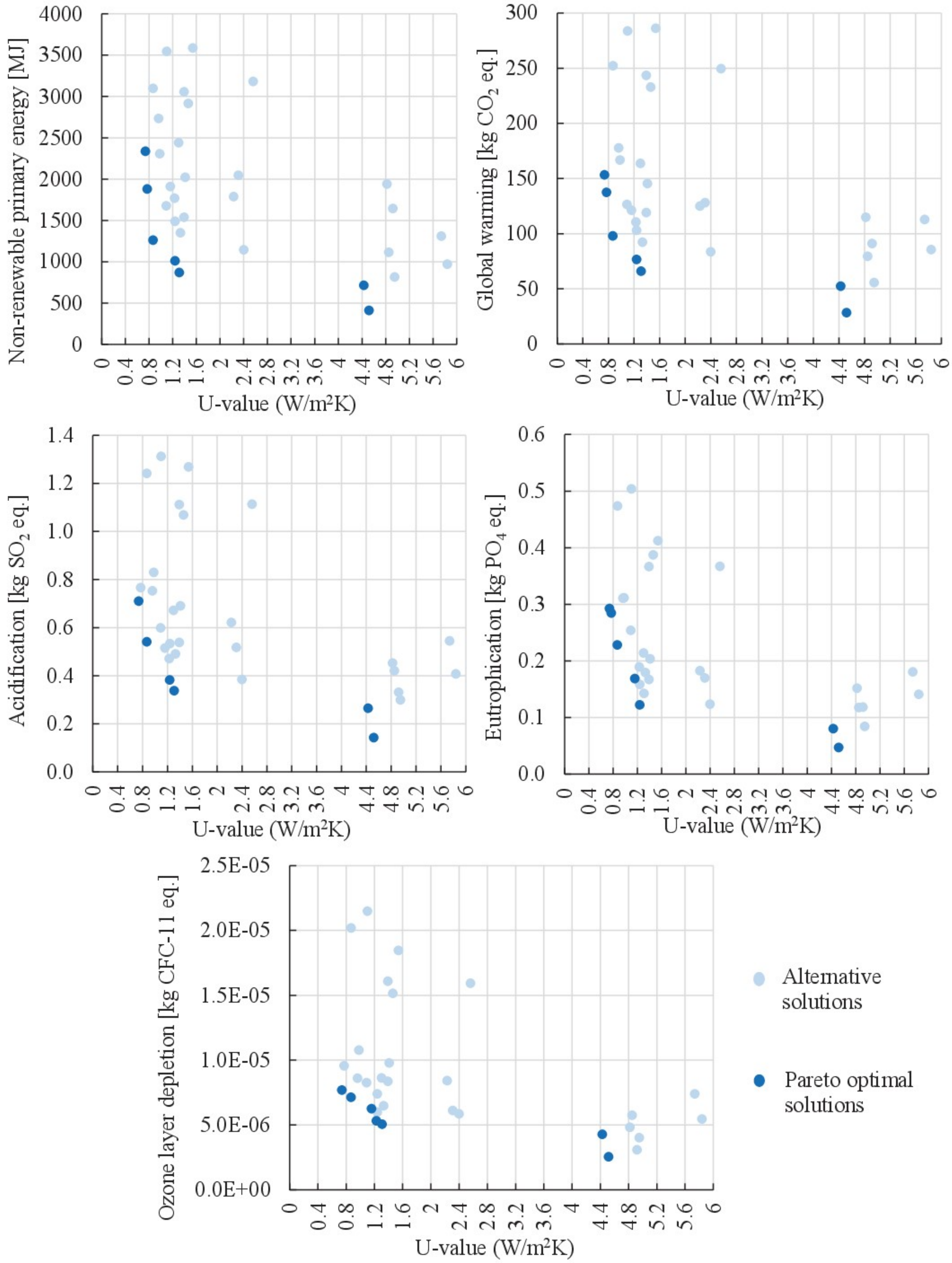


Figure 2.8 Thermal transmittance and embodied impacts trade-offs for the alternative window solutions, with Pareto optimal solutions highlighted in dark blue

Figure 2.9 identifies the set of non-dominated window solutions positioned on the Pareto optimal frontiers and shows the trade-off between the U-value and embodied impacts. In the set of non-dominated window solutions of the two-dimensional objective space for the five environmental categories, the following four window solutions are common to all categories: a low-E coated triple-glazing (Triple A, non-tempered and laminated) with wood frame (WOO.SDT_TA) or with PVC frame (PVC.T_TA); and two types of single-glazed solution with wood frame (WOO.SDT_SA and WOO.SDT_SB).

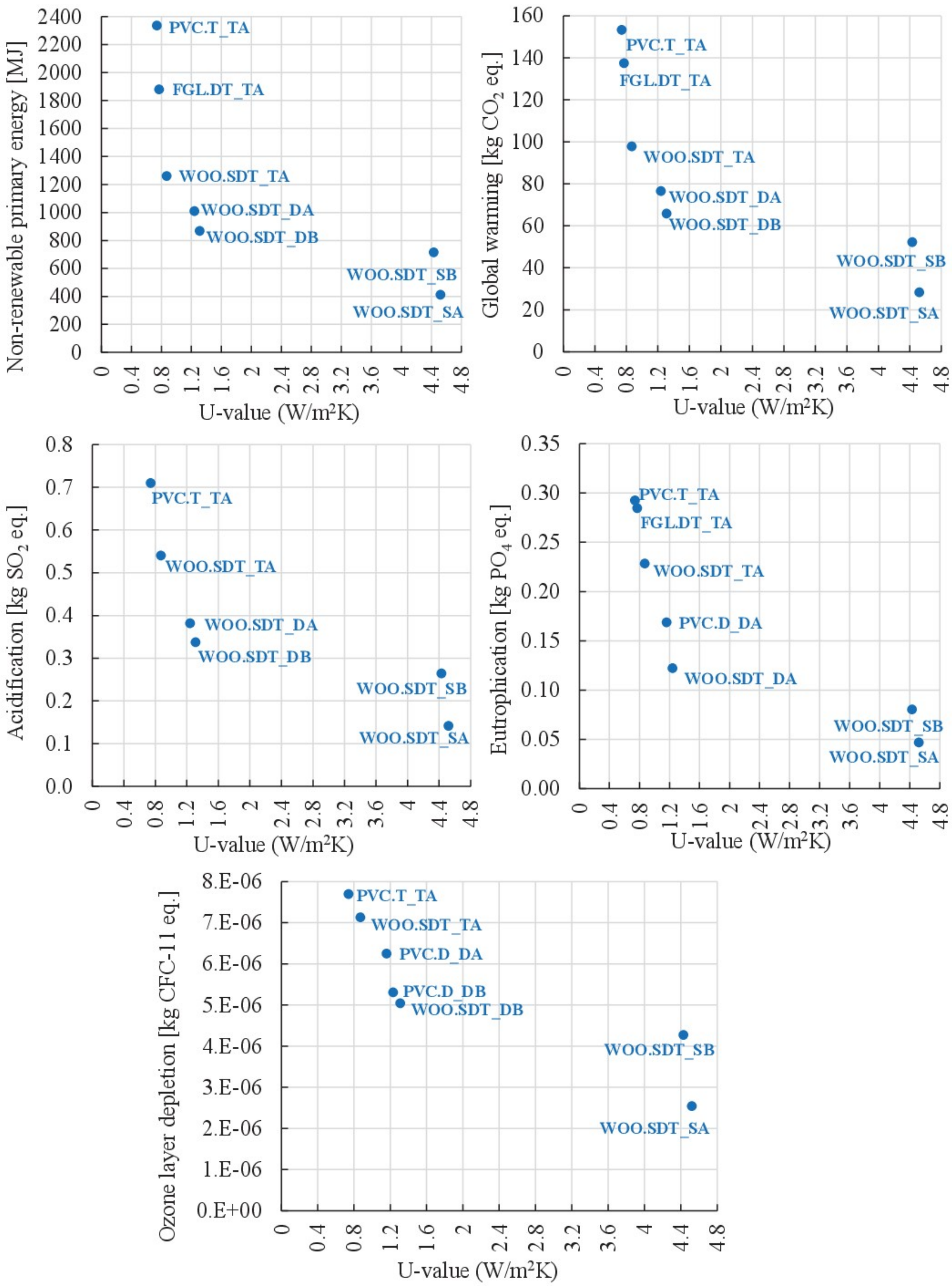


Figure 2.9 Pareto optimal frontiers (thermal transmittance vs. environmental impacts)

The Pareto optimal frontier consists of supported and unsupported non-dominated solutions. The supported and unsupported non-dominated solutions for non-renewable primary energy and for global warming are the same. The set of supported non-dominated solutions is composed of a low-E coated triple-glazing (Triple A) with wood, PVC or fiberglass frame, and a low-E coated double-glazing (Double B) and a single glazing (Single A) with wood frames. The set of unsupported non-dominated solutions consists of a double-glazed solution with solar control film (Double A) and a single-glazed solution with solar control film (Single B) with wood frames. For eutrophication, the low-E coated double-glazing (Double B) is not positioned on the Pareto optimal frontier; instead a double-glazed solution with solar control film (Double A) with wood frame (as a supported non-dominated solution) and with PVC frame (as an unsupported non-dominated solution) appear on the Pareto optimal frontier. Regarding acidification and ozone layer depletion, the low-E coated triple-glazing (Triple A) with fiberglass frame is not located on the Pareto optimal frontier. The set of unsupported non-dominated solutions for ozone layer depletion comprises PVC- framed windows with two types of double-glazed solutions, Double A and Double B, and a wood-framed window with a single-glazing (Single B).

2.4. Concluding remarks

This chapter proposes an approach based on embodied impact assessment and Pareto optimal frontier to support environmentally friendly design of windows. A comprehensive assessment of the embodied environmental impacts of 32 window systems (four alternative framing and eight glazing solutions) was implemented. The most common framing materials (aluminum, fiberglass, PVC and wood) with other components (spacer, thermal break, weather stripping etc.), and single-, double-, and tripled-glazed solutions (with coatings and gas-filled cavities) have been thoroughly assessed to ascertain the contribution of each component to the overall embodied impacts of the window system.

The embodied impacts calculated for the window systems show that for aluminum windows the contribution of the frame (>60% in all categories) is more significant than the glazing, while for wood-framed windows, the contribution of the framing is much less significant (<30% in all categories). For the PVC and fiberglass windows, the contribution of the framing varies depending on the glazing solution.

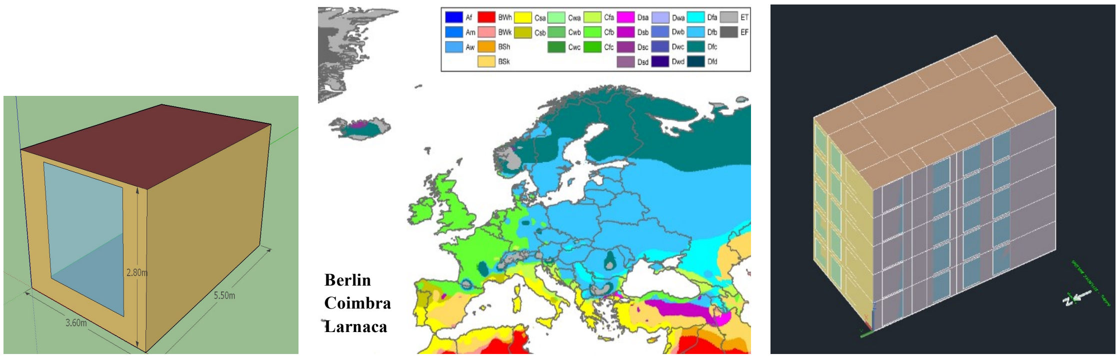
The assessment of the glazing alternatives shows that the embodied impacts are highly influenced by the type of glass. Tempered glass leads to higher embodied impacts for the five categories due to the tempering process. For laminated glass, a polyynyl butyral (PVB) interlayer, 0.38 mm thick, accounts for about 20% of total global warming (GW) and non-renewable primary energy (NRPE) embodied impacts. It should also be noted that the glass coating is one of the components with highest eutrophication (EU) impact due to the electricity consumed in the production process. A low-E film (copper oxide) contributes to approximately 35% of the total embodied eutrophication of the glazing system.

Regarding the framing materials, wood has the lowest embodied impacts, while aluminum frame has the highest. In the aluminum frame, the thermal break is responsible for up to 23% of the embodied impacts. Results for PVC frames show that the stainless steel used to ensure good mechanical resistance reaches a share of up to 29% of the embodied impacts.

Finally, Pareto optimal frontiers have been calculated so as to identify the set of non-dominated window solutions, showing the trade-off between thermal transmittance and embodied impacts (five categories). The results from the embodied impact assessment of windows show that four window solutions are on the Pareto frontier for all categories: a low-E coated triple-glazing (Triple A, non-tempered and laminated) with a wood or PVC frame and two single-glazed solutions with wood frame.

The approach proposed in this chapter can help decision makers to choose windows according to the preferred objectives. This approach can be extended and applied to other window solutions, and to different desired objectives. The development of windows is commonly and mainly based on architectural, mechanical, thermal, and acoustical requirements. As environmental impacts and sustainability is of paramount importance, this chapter proposes an embodied impacts approach that can be applied during windows design to support the identification of components more environmentally friendly. To further improve the proposed framework, the full life cycle should be addressed to calculate overall environmental impacts and costs.

3. Integrated environmental, energy and cost life cycle analysis of windows[2]



Abstract The main goal of this chapter is to present an integrated cost and environmental LCA of alternative windows for an office use located in three European climates. This chapter builds on the embodied impact assessment (presented on the previous chapter) and the operational impact assessment. This chapter presents a comprehensive complementary analysis of different window solutions combining alternative glazing and framing options to identify opportunities to minimize life cycle environmental and cost impacts. Moreover, it investigates how various window properties influence the economic and environmental performance of building windows and support decision-making.

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[2] Based on: Saadatian, S., Simões, N., Freire, F. (2021). "Integrated environmental, energy and cost life-cycle analysis of windows: Optimal selection of components", Building and Environment, vol. 188, Article 107516. https://doi.org/10.1016/j.buildenv.2020.107516 (Saadatian et al., 2021b)

3.1. Introduction

Windows are essential components of the building envelope since they influence the building's thermal performance and provide lightning and ventilation. Heat transfer through windows can account for a significant share of the overall energy needs of buildings or contribute to the need for additional heating and cooling. However, modern energy-efficient windows are costly and require significant quantities of materials. Thus, proper strategies should be used to wisely select optimal windows that minimize energy consumption, costs, and environmental impacts throughout their life cycle (Rodrigues et al., 2018).

The thermal transmittance value (U-value) and solar factor (g-value) are the properties with an important role in the energy balance of windows. However, research on the influence of the window properties has mainly focused on the operational energy performance of windows (Tsikaloudaki et al., 2012; Yeom et al., 2020), overlooking life cycle environmental impacts and costs. In addition, much of the current literature on window properties tends to focus on a single element of windows (Souviron et al., 2019), with most authors concentrating on the framing (Carlisle and Friedlander, 2016; Recio et al., 2005; Sinha and Kutnar, 2012; Tarantini et al., 2011), a few on the glazing (Babaizadeh and Hassan, 2013; Syrrakou et al., 2005), and shading (Babaizadeh et al., 2015; Invidiata and Ghisi, 2016; Sanati and Utzinger, 2013). The rest have studied whole windows rather than addressing the impacts of individual components (Baldinelli et al., 2014; Menzies and Wherrett, 2005; Minne et al., 2015).

There has been an increasing amount of literature on the environmental performance of windows. Much of this literature has paid particular attention to the environmental impacts in the operation phase (Litti et al., 2018; Papaefthimiou et al., 2009) and very few studies have investigated the embodied impacts of windows (Seo et al., 2015; Sinha and Kutnar, 2012), while the environmental performance of windows over their complete life cycle has been overlooked. Several attempts have been made, however, to investigate the economic performance of windows without looking at the environmental performance. Menzies and Wherrett (Menzies and Wherrett, 2005) investigated the energy and cost savings that might be achieved in the design and selection of sustainable multi-glazed windows. Jaber and Ajib (Jaber and Ajib, 2011) identified the optimum window type and size to reduce both energy and investment costs for three climate zones (Amman, Aqaba, and Berlin).

Environmental and cost life cycle assessment can be integrated to explore the most influential window properties (U- and g-value) and components (glass and frames) in terms of the economic and environmental performance and to estimate the environmental and cost benefits of the window solutions

(Khasreen et al., 2009; Salazar, 2014). So far, Minne et al. (Minne et al., 2015) applied an integrated environmental and cost life cycle analysis to alternative windows for a single-family home in various US climate regions. However, the contribution of individual window components (glass and frames), as well as the influence of window properties (U- and g-value) to the life cycle cost and environmental impacts have not been presented.

Along with the thermal transmittance and solar factor for windows, orientation, and climate data are significant factors for the life cycle cost and environmental impacts of a window. The energy performance of a window depends not only on the window properties but also on its orientation and the climatic conditions of the location (Banihashemi et al., 2015; Burgett et al., 2013). A considerable amount of literature has studied the effect of window orientation and climatic conditions on the operational performance of buildings (lighting, heating, and cooling load). Mangkuto et al. (Mangkuto et al., 2016) investigated the influence of window area and orientation on the various daylight metrics and lighting energy demand in buildings. The results showed that the optimal window solutions in terms of daylight metrics and lighting energy demands were South-facing windows with about 30% window-to-wall ratio. Alghoul et al. (Alghoul et al., 2017) assessed the influence of window area and orientation on the heating and cooling energy consumption of an office in Libya. Several studies have looked at the influence of window orientation and climatic conditions on the operational energy and life cycle cost (Pikas et al., 2014; Schwartz et al., 2016; Thalfeldt et al., 2013; Yasar and Kalfa, 2012). For example, Pikas et al. considered possible window design solutions and orientations for the office buildings in the cold Estonian climate, taking both cost optimality and energy efficiency into account. Yasar et al. used energy simulation software to investigate the effects of different glazed units and orientations on the energy needs and operating cost of high-rise residential buildings in moderate-humid climate regions of Turkey.

The operational stage is generally the main contributor to the total life cycle impacts; however, if windows are more energy efficient the contribution of embodied impacts increases. This aspect has not been thoroughly analyzed and as mentioned before, the literature has mainly focused on the operational performance of windows. Furthermore, there have been no comparative life cycle studies on windows that investigate the influence of high versus low U- and g-values, together with the effect of orientation and climate data on both economic and environmental life cycle assessment. Thus, a comprehensive life cycle analysis should be performed to inform the wise selection of windows, considering their properties and components.

This chapter presents an integrated cost and environmental life cycle analysis of window solutions combining alternative glazing and framing options for office use. Pareto optimal window solutions were selected using a bi-objective optimization (costs vs. environmental impacts), considering various orientations and three different European climate regions. The influence of each window component (glass and frames), as well as window properties (U- and g-value) on the overall environmental and cost life cycle assessment was investigated.

3.2. Materials and methods

An integrated environmental, energy and cost life cycle analysis was implemented to calculate the cost and environmental impacts of alternative windows for a reference office room. Thermal dynamic simulation was employed to calculate operational energy using a calculation model and validated with respect to EN 15265 (2007). This European Standard defines assumptions, boundary conditions and 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. The reference room model was verified through application to a reference office building introduced by Corgnati et al. (2013). Finally, a bi-objective optimization problem (costs vs. environmental impacts, for selected impact categories) was solved using Pareto optimal frontiers.

3.2.1. Life cycle model and inventory

A life cycle model and inventory were developed and implemented for 32 alternative window solutions (combining glazing and framing options), in a standard size (1.23 m × 1.48 m, based on ISO 10077-1 (2017)). The functional unit selected was the total office area (19.80 m^2) over a period of 30 years, occupied by one person during working hours. The service life of a building is defined by its design, the construction methods and solutions used, user behavior, and maintenance strategy. Some of those factors are difficult to predict, so this research follows many other studies that have also assumed a 30-year lifespan for office buildings (Ajayi et al., 2019; Basbagill et al., 2013; Minne et al., 2015). The life cycle model included the construction phase (for the opaque envelope of the office with alternative windows) and operation phase (for heating and cooling).

3.2.1.1. Window solutions and office room

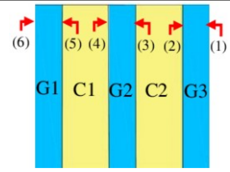
The reference room is described in ISO 13791 (2004), 5.50 m long, 3.60 m wide and with a height of 2.80 m. All opaque components of the room were considered as adiabatic, excluding the front wall (3.60 m × 2.80 m). Thermo-physical properties of the opaque elements of the room (listed in Table 3.1), were taken from the standard.

Table 3.1 Thermo-physical properties of the opaque elements of the reference office room (ISO 13791 (2004))

Structure	Thickness, [m]	Thermal conductivity, λ (W/(m. K))	Density, ρ (kg/m^3)	Specific heat, C_p (kJ/(kg. K))
Front wall				
Outer layer	0.115	0.99	1800	0.85
Insulation layer	0.060	0.04	30	0.85
Masonry	0.175	0.79	1600	0.85
Internal plastering	0.015	0.70	1400	0.85
Adiabatic walls				
Gypsum Plaster	0.012	0.21	900	0.85
Insulation layer	0.100	0.04	30	0.85
Gypsum Plaster	0.012	0.21	900	0.85
Ceiling / Floor				
Plastic covering	0.004	0.23	1500	1.50
Cement Floor	0.060	1.40	2000	0.85
Insulation layer	0.040	0.04	50	0.85
Concrete	0.180	2.10	2400	0.85

Table 3.2 shows the 41 cases studied: 32 alternative window solutions (4 frames × 8 glazing systems) + 8 glazing systems (without frame) + 1 baseline (wall without any window). The glazing solutions were selected based on low and high values for the thermal transmittance (U-value) and solar factor (g-value), within the commercially available range for different glazing types (single, double and triple) based on the Saint-Gobain Glass library (Saint-Gobain Glass, 2019), a leading manufacturer of flat glass for the European market. Cavities between the panes of glass were assumed to be filled with Argon gas. The alternative frame materials selected were aluminum (ALU), polyvinyl chloride (PVC), fiberglass (FGL) and wood (WOO). In addition, each glazing solution without a frame was considered (no framing windows, NOF), so as to compare the glazing solutions without the influence of the frame.

Table 3.2 Properties of the alternative window solutions selected

Window ID[1]	Glass layers (Glazing solution ID)	Glass type	Thickness guide in mm G_1-C_1-G_2-C_2-G_3 [2]	Coating type (coated surface number) [3]	Frame material (Framing ID)	U-value $W/(m^2K)$	g-value
							
NOF.S_SA[4]					no frame (NOF.S)	5.80	
ALU.S_SA					Aluminum (ALU.S)	5.84	
PVC.S_SA	Single (SA)	Annealed (A)	4A	-	PVC (PVC.S)	4.92	0.88
FGL.SD_SA					Fiberglass (FGL.SD)	4.95	
WOO.SDT_SA					Wood (WOO.SDT)	4.52	
NOF.S_SB					no frame (NOF.S)	5.60	
ALU.S_SB					Aluminum (ALU.S)	5.74	
PVC.S_SB	Single (SB)	Annealed (A)	8A	Solar control (2)	PVC (PVC.S)	4.82	0.39
FGL.SD_SB					Fiberglass (FGL.SD)	4.85	
WOO.SDT_SB					Wood (WOO.SDT)	4.43	
NOF.D_DA					no frame (NOF.D)	1.00	
ALU.D_DA					Aluminum (ALU.D)	1.39	
PVC.D_DA	Double (DA)	Annealed (A)	6A-15-4A	Solar control (2)	PVC (PVC.D)	1.16	0.33
FGL.SD_DA					Fiberglass (FGL.SD)	1.24	
WOO.SDT_DA					Wood (WOO.SDT)	1.24	
NOF.D_DB					no frame (NOF.D)	1.10	
ALU.D_DB					Aluminum (ALU.D)	1.46	
PVC.D_DB	Double (DB)	Annealed (A)	4A-16-4A	Low-e (3)	PVC (PVC.D)	1.23	0.65
FGL.SD_DB					Fiberglass (FGL.SD)	1.33	
WOO.SDT_DB					Wood (WOO.SDT)	1.31	
NOF.D_DC					no frame (NOF.D)	1.20	
ALU.D_DC					Aluminum (ALU.D)	1.54	
PVC.D_DC	Double (DC)	Tempered (T)	6T-12-6T	Solar control (2)	PVC (PVC.D)	1.30	0.35
FGL.SD_DC					Fiberglass (FGL.SD)	1.41	
WOO.SDT_DC					Wood (WOO.SDT)	1.39	
NOF.D_DD					no frame (NOF.D)	2.60	
ALU.D_DD					Aluminum (ALU.D)	2.56	
PVC.D_DD	Double (DD)	Laminated (L)	4A-16-6.4L	-	PVC (PVC.D)	2.31	0.78
FGL.DT_DD					Fiberglass (FGL.DT)	2.23	
WOO.SDT_DD					Wood (WOO.SDT)	2.40	
NOF.T_TA					no frame (NOF.T)	0.50	
ALU.T_TA					Aluminum (ALU.T)	0.87	
PVC.T_TA	Triple (TA)	Annealed (A)	4A-18-4A-18-4A	Low-e (2&5)	PVC (PVC.T)	0.74	0.62
FGL.DT_TA					Fiberglass (FGL.DT)	0.77	
WOO.SDT_TA					Wood (WOO.SDT)	0.87	
NOF.T_TB					no frame (NOF.T)	0.80	
ALU.T_TB					Aluminum (ALU.T)	1.10	
PVC.T_TB	Triple (TB)	Laminated (L)	6.8L-10-4A-10-4A	Low-e (2&5)	PVC (PVC.T)	0.96	0.58
FGL.DT_TB					Fiberglass (FGL.DT)	0.98	
WOO.SDT_TB					Wood (WOO.SDT)	1.09	

[1] Window system ID is expressed as frame ID_glazing ID.

[2] G_1: 1st glass pane thickness & type, C_1: 1st cavity thickness, G_2: 2nd glass pane thickness & type, C_2: 2nd cavity thickness, G_3: 3rd glass pane thickness & type.

[3] Glass surfaces are identified by number, starting with the exterior surface.

[4] NOF stands for no frame, ALU for aluminum, PVC for polyvinyl chloride, FGL for fiberglass, and WOO for wood framing.

The construction phase of the opaque envelope with the alternative windows includes raw material extraction and transport to the production site, production of the materials and their transport to the building site by lorry (Spielmann et al., 2007). Table 3.3 presents the bill of materials for the front wall including the opaque envelope and alternative windows. Technical data of the opaque components was taken from Classen et al. (Classen et al., 2009); Hischier and Gallen (Hischier and Gallen, 2007); Kellenberger et al. (Kellenberger et al., 2007); and Werner et al. (Werner et al., 2007), framing from producers and suppliers, and glazing from the relevant environmental product declarations (EPDs) (Saint-Gobain Glass, 2019). The front wall of the office room without a window was also considered (entirely opaque envelope) to better understand the economic and environmental influence of the windows used for the office room.

Table 3.3 Bill of materials for the front wall (10.08 m^2) including the opaque elements and alternative windows (1.82 m^2): i) opaque envelope; ii) unframed window; iii) aluminum-framed window; iv) PVC-framed window; v) fiberglass-framed window; vi) wood-framed window.

i) opaque envelope

Opaque envelope area, m^2	Mass of opaque components (kg)			
	Internal plastering	Insulating layer	Masonry	Outer layer
10.08 (no window)	211.68	18.14	2822.40	2086.56
8.26 (with window)	173.46	14.87	2312.80	1709.82

ii) unframed window

Window components	Mass of window components (kg)							
	NOF.S_SA[1]	NOF.S_SB	NOF.D_DA	NOF.D_DB	NOF.D_DC	NOF.D_DD	NOF.T_TA	NOF.T_TB
Glazing	18.20	36.40	46.66	37.66	55.58	46.89	58.11	66.28

iii) aluminum-framed window

Window components	Mass of window components (kg)							
	ALU.S_SA[2]	ALU.S_SB	ALU.D_DA	ALU.D_DB	ALU.D_DC	ALU.D_DD	ALU.T_TA	ALU.T_TB
Glazing	15.19	30.38	35.21	28.43	41.96	35.40	45.08	51.42
Framing	7.75	8.14	22.64	22.65	22.64	22.61	22.00	22.31

iv) PVC-framed window

Window components	Mass of window components (kg)							
	PVC.S_SA	PVC.S_SB	PVC.D_DA	PVC.D_DB	PVC.D_DC	PVC.D_DD	PVC.T_TA	PVC.T_TB
Glazing	14.61	29.22	34.51	27.85	41.12	34.67	41.51	47.35
Framing	36.02	36.23	25.99	26.01	25.99	25.95	32.07	29.88

v) fiberglass-framed window

Window components	Mass of window components (kg)							
	FGL.SD_SA	FGL.SD_SB	FGL.SD_DA	FGL.SD_DB	FGL.SD_DC	FGL.DT_DD	FGL.DT_TA	FGL.DT_TB
Glazing	15.10	30.20	38.71	31.25	46.11	33.37	41.35	47.18
Framing	13.24	13.17	12.89	12.92	12.89	18.75	18.02	18.37

vi) wood-framed window

Window components	Mass of window components (kg)							
	WOO.SDT_SA	WOO.SDT_SB	WOO.SDT_DA	WOO.SDT_DB	WOO.SDT_DC	WOO.SDT_DD	WOO.SDT_TA	WOO.SDT_TB
Glazing	13.46	26.92	34.51	27.85	41.12	34.58	42.98	49.02
Framing	17.40	17.26	16.68	16.72	16.68	16.63	15.88	16.34

[1]NOF stands for no frame, ALU for aluminum, FGL for fiberglass, and WOO for wood framing.

[2]Window IDs and the detailed information are presented in Table 3.2.

3.2.1.2. Operation phase

The operation phase was associated with the energy used for heating and cooling the office room with the alternative window solutions. For the occupancy pattern, the room was assumed to be occupied by one person from 8 am to 6 pm (in working days). The interior seasonal setpoints were considered as 20 °C for the heating season and 25 °C for the cooling season, with a ventilation rate of 0.4 air changes per hour from 8 am to 6 pm during weekday. A seasonal coefficient of performance (SCOP) of 3.40 for the heating season and a seasonal energy efficiency ratio (SEER) of 5.10 for the cooling season were adopted in accordance with energy efficiency class A (European Union, 2011). Four cardinal directions for the window orientations were evaluated as well.

Three European locations were studied, considering different heating degree days (HDD) and cooling degree days (CDD), according to the Köppen−Geiger Climate Classification (Kottek et al., 2006; Rubel et al., 2017). The selected climate zones were categorized under the Köppen–Geiger classification system: a temperate climate with Mediterranean hot summer (Csa) represented by Portugal (Coimbra); a temperate oceanic climate (Cfb) represented by Germany (Berlin); and a semi-arid (steppe) desert climate (BSh) represented by Cyprus (Larnaca).

The energy needs (heating and cooling) of the room were calculated using EnergyPlus™ software (U.S. Department of Energy, 2019). The life cycle impacts per kWh of the annual electricity supply mix was calculated for Portugal based on Garcia et al. (Garcia et al., 2014), and for Germany and Cyprus based on ecoinvent v.3.2. database (ecoinvent centre, 2015).

3.2.1.2.1. Validation procedure of the simulation results with respect to CEN Standard

A set of assumptions, requirements and validation tests was identified by the European Standard (CEN, 2007a) for procedures applied to calculate the annual energy needs for space heating and cooling of a room in a building. This standard aims to calculate annual heating/cooling energies for the reference office room with given test cases, and to achieve desired accuracy compared to reference results given in kWh.

A room located in Trappes, France (49°N, 2°E) with 7 m^2 window glazing was considered facing West. Two types of window glazing were introduced: a double pane glass with external shading device (shaded DP, U=2.37 W/(m^2K), g=0.20) and a double pane glass without external shading device (DP, U=2.93 W/(m^2K), g=0.77). The initial test (Test 1) was considered as the basic operation of the calculation method and then following tests were defined based on the initial test. The glazing system was selected with the external shade (shaded DP). Internal gains were considered 20 W/m^2, from 8 am to 6 pm during weekdays. Ventilation rate was considered as 1 air change per hour from 8 am to 6 pm during weekdays, and no infiltration. The continuous system air temperature control was assumed for operation all days of the week, with 20 °C set point for heating and 26 °C set point for cooling.

The calculation results for heating (Q_H) and for cooling (Q_C) are compared to the sum of the reference values ($Q_{H,ref}$ and $Q_{C,ref}$) with following equations (CEN, 2007a):

$r_{QH} = ABS\ (Q_H - Q_{H,ref}) / Q_{tot,ref}$,   (for heating)

$r_{QC} = ABS\ (Q_C - Q_{C,ref}) / Q_{tot,ref}$,   (for cooling)

The required accuracy levels for all tests are the following:

- Level A: $r_{QH} \leq 0.05$ and $r_{QC} \leq 0.05$

- Level B: $r_{QH} \leq 0.10$ and $r_{QC} \leq 0.10$

- Level C: $r_{QH} \leq 0.15$ and $r_{QC} \leq 0.15$

Validation tests must be within at least accuracy level C.

3.2.1.2.2. Verification of reference room model – application to a reference building

A reference building introduced by Corgnati et al. (2013) has been presented as the second case study in order to assess the behavior of the window solutions within a different building. The reference office building has been simulated under the same conditions of the reference room with the same window solutions, in order to verify the results achieved from the reference room. The office building has a rectangular plan with 5 floors above ground and a covered area of 2400 m^2. The reference office building scheme and the constructions characteristics are presented in Appendix II (Figure A. 1 and Table A. 1).

The orientation weighting factors for the reference room were defined according to the ordinary windows distribution in the reference office building. Table 3.4 presents the weighting factors assigned to each orientation of the reference room.

Table 3.4 Weighting factors assigned to each orientation of reference room

Orientation	Weighting factor
North	0.180
East	0.318
South	0.184
West	0.318

3.2.2. Environmental life cycle impact assessment methods

The following five impact categories were selected: cumulative energy demand (CED) for calculating non-renewable primary energy (NRPE) (Frischknecht et al., 2007), global warming (GW, time horizon of 100 years), acidification (AC), eutrophication (EU) and ozone layer depletion (OD), from the CML 2001 method developed by the Institute of Environmental Sciences of the University of Leiden (Bruijn et al., 2002). The selected impact categories follow the European standards: EN 15804 (2012) and EN 15978 (2011), and are commonly used in building life cycle studies (Monteiro et al., 2016; Rodrigues et al., 2018). The LCA model and calculations have been performed using the SimaPro software.

3.2.3. Life cycle costing method

Life cycle costing was performed to calculate the global cost (€) in terms of net present value for the alternative window solutions, addressing the relevant costs, namely, construction costs (initial investment for the opaque envelope and alternative window solutions), and operational energy costs (covering both heating and cooling). The global cost calculation method followed by the Commission Delegated Regulation (EU) No 244 (European Commission, 2012) includes the present value of the initial investment costs, running costs, and replacement costs if applicable.

A 3% discount rate has been assumed. Since the initial investment costs of the opaque envelope did not vary, the research focused on how the cost of the individual window components influenced the life cycle cost results. The initial investment costs for the opaque envelope (65 €/m^2) and window solutions (as listed in Table 3.5) were provided by manufactures and suppliers. The electricity costs were derived from the European electricity price statistics for the three European climate zones: 0.229 €/kWh for Portugal, 0.300 €/kWh for Berlin, and 0.218 €/kWh for Cyprus (Eurostat, 2019).

Table 3.5 The initial investment costs for the alternative window solutions (€/1.82 m^2 window)

i) unframed window								
Window components	Cost of window components (€/1.82 m^2 window)							
	NOF.S_SA[1]	NOF.S_SB	NOF.D_DA	NOF.D_DB	NOF.D_DC	NOF.D_DD	NOF.T_TA	NOF.T_TB
Glazing cost	33.59	134.35	167.93	67.17	257.50	78.37	123.15	156.74
ii) aluminum-framed window								
Window components	Cost of window components (€/1.82 m^2 window)							
	ALU.S_SA[2]	ALU.S_SB	ALU.D_DA	ALU.D_DB	ALU.D_DC	ALU.D_DD	ALU.T_TA	ALU.T_TB
Glazing cost	28.03	112.14	126.79	50.72	194.41	59.17	95.55	121.61
Framing cost	571.95	571.95	473.55	473.55	473.55	473.55	861.00	861.00
iii) PVC-framed window								
Window components	Cost of window components (€/1.82 m^2 window)							
	PVC.S_SA	PVC.S_SB	PVC.D_DA	PVC.D_DB	PVC.D_DC	PVC.D_DD	PVC.T_TA	PVC.T_TB
Glazing cost	26.95	107.79	124.19	49.68	190.43	57.96	87.94	111.93
Framing cost	248.58	248.58	261.01	261.01	261.01	261.01	285.87	285.87
iv) fiberglass-framed window								
Window	Cost of window components (€/1.82 m^2 window)							

components	FGL.SD_SA	FGL.SD_SB	FGL.SD_DA	FGL.SD_DB	FGL.SD_DC	FGL.DT_DD	FGL.DT_TA	FGL.DT_TB
Glazing cost	27.85	111.41	139.26	55.70	213.53	55.77	87.63	111.53
Framing cost	496.21	496.21	496.21	496.21	496.21	432.10	432.10	432.10

v) wood-framed window

Window	Cost of window components (€/1.82 m² window)							
components	WOO.SDT_SA	WOO.SDT_SB	WOO.SDT_DA	WOO.SDT_DB	WOO.SDT_DC	WOO.SDT_DD	WOO.SDT_TA	WOO.SDT_TB
Glazing cost	24.84	99.35	124.19	49.68	190.43	57.96	91.07	115.91
Framing cost	625.00	625.00	625.00	625.00	625.00	625.00	625.00	625.00

[1] NOF stands for no frame, ALU for aluminum, FGL for fiberglass, and WOO for wood framing.

[2] Window IDs and the detailed information are presented in Table 3.2.

3.2.4. Pareto optimal frontiers

The concept of the Pareto optimal frontier (a set of non-dominated, non-inferior, or efficient solutions) introduces mathematical fundamentals for multi-objective problems. A solution is non-dominated when there is no other feasible solution that simultaneously ameliorates all the objective function values. In other words, ameliorating one of the objectives involves worsening at least one of the other objective function values (Antunes et al., 2016).

In this chapter, the Pareto optimal frontier method was applied to a bi-objective problem (costs vs. environmental impacts, for each of the five selected impact categories). Pareto-optimal solutions are selected following the concept of dominance among vectors in the objective space (Sánchez et al., 2016) which has already been described in subsection 2.2.4 and shown by Figure 2.4.

3.3. Results and discussion

This section presents the main results. Section 3.3.1. presents primarily the environmental life cycle impact assessment results, and finally the validation tests based on EN 15265 (2007) and verification of the reference room model with a reference building. Section 3.3.2 presents the life cycle costing results. Lastly, Pareto optimal frontiers are presented in Section 3.3.3, based on the bi-objective optimization problem (costs vs. environmental impacts, for the five selected impact categories) to identify Pareto optimal window solutions.

3.3.1. Environmental life cycle impact assessment

The life cycle assessment of the components (opaque envelope, glazing and framing) and processes (construction and operation) were performed for the selected environmental impact categories, for the front wall with alternative windows and different orientations in the same climate region (Coimbra). Figure 3.1 presents the life cycle environmental impacts of the 30-year use of the office room, comparing the alternative windows when fully exposed to the sun (no obstacle) from each of the four cardinal directions. Additional detailed information for Figure 3.1 with the full results is documented in Appendix II (Table A. 2).

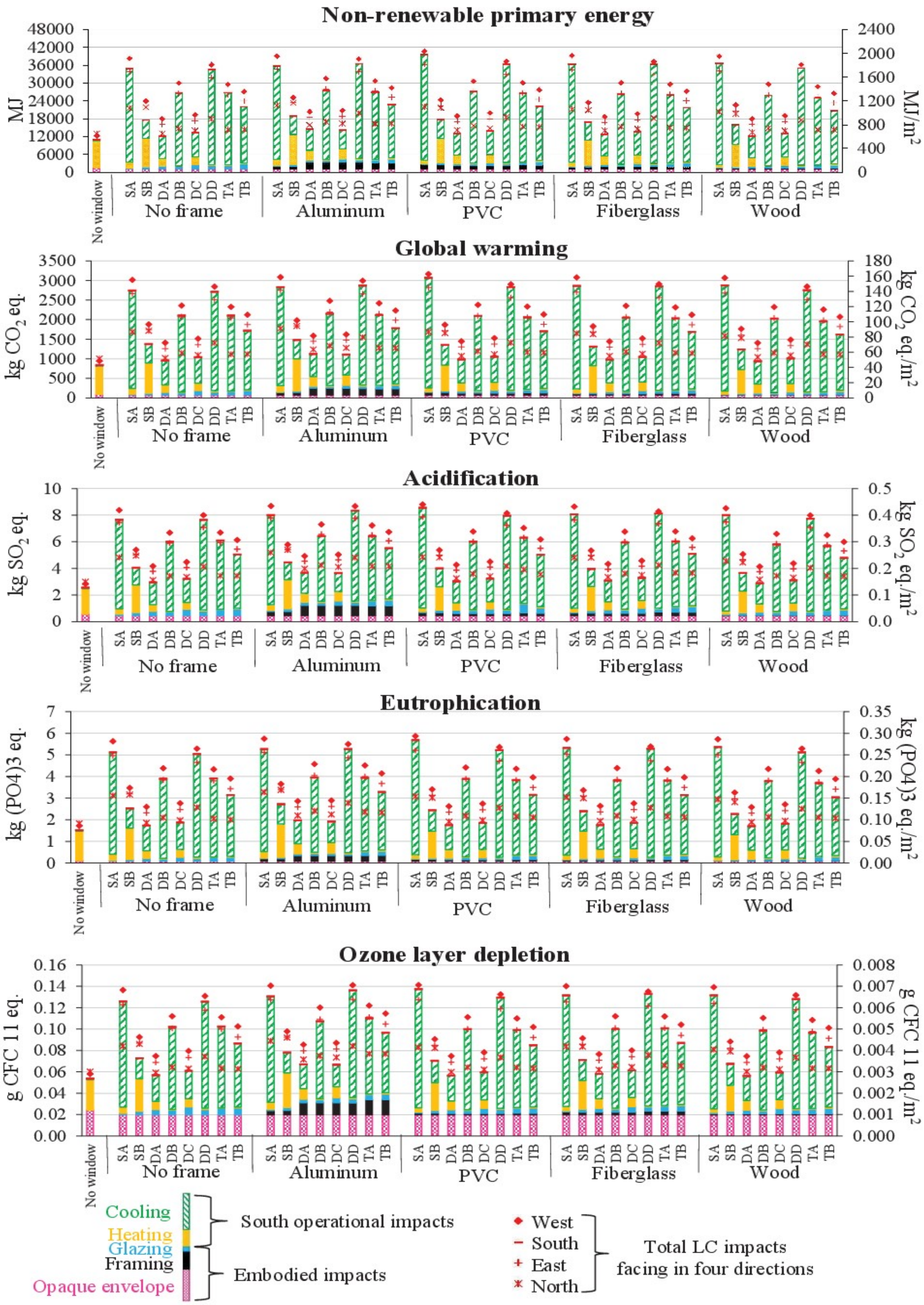


Figure 3.1 Life cycle environmental impacts of 30-year use of the office room in Coimbra, comparing different window solutions facing in four directions (a table with full results is presented as supplementary material)

The results are also presented by square meter of floor area for easier interpretation and comparison with other studies (as a secondary axis). The comparative assessment for the embodied impacts of the unframed windows shows that the double-glazing solution using tempered glass (referenced as DC) and the triple glazing solutions (referenced as TA, TB) have the highest embodied impacts of all the solutions. The glazing solutions with low-e coating (DB, TA, TB, refer to Table 3.2) show significant EU embodied impacts, due to the electricity used in the production of the coating. The low-e film (copper oxide) contributes approximately 35% of the total embodied EU of the glazing system because copper provides the eutrophic conditions by depleting dissolved oxygen. The comparative assessment for the operational impacts of the unframed windows indicates that the glazing solutions with the lowest solar factor (SB, DA, DC, g-value<0.40) have lower operational (cooling) impacts, under direct exposure to the sun.

The comparative assessment for the embodied impacts of the framing options shows that wood is the option with the lowest embodied impacts for the five impact categories. The aluminum frame for the double- and triple-glazed solutions has the highest impacts in all categories. Compared with the embodied impacts of the unframed window solutions, adding the wood frame to each solution leads to a 14-24% reduction of the embodied impacts for the whole window, within all impact categories, while the aluminum frame leads to a 29-49% increase in the total embodied impacts.

The total embodied impact assessment involving the embodied impacts of the front wall with alternative windows shows that the aluminum frame for the double- and triple-glazed window solutions has the highest embodied impacts for all impact categories (51–62% of total embodied impacts), except for OD impacts. Conversely, the wood frame contributes the least (7–9%) to the total embodied impacts. Although the opaque envelope was a fixed variable in this study, its contribution to the total OD embodied emissions is acknowledged, owing to the insulating layer.

The total life cycle impact assessment (embodied and operational) of the wall with framed window solutions facing South shows that the total embodied impacts of the wall with aluminum-framed windows contribute about 16-31% to the total life cycle impacts, while the figure for the PVC and fiberglass-framed windows is about 8-23%, and around 5-17% for wood-framed solutions. The glazing solutions with the highest solar factor (SA, DB & DD, g-value>0.40) have the most influence on the upper cooling energy needs of the room. The operational impacts from cooling accounts for 51–92% of total life cycle impacts, within all impact categories. The comparison between the operational impacts of the unframed glazing solutions and the framed ones indicates that the frame option leads to slight differences in the operational impacts.

The results of comparing the different orientations show that for the West orientation, all windows (except a single-glazed one with low g-value) have higher total life cycle impacts thanks to the higher cooling energy needs. Window solutions with the lowest solar factor (g-value<0.40) that face West offer considerably higher benefits than the other solutions, compared with the other orientations. For example, a low-solar factor window (ALU.D_DA; g-value 0.33) has 7% lower life cycle NRPE impacts for the North orientation and 35% for the West orientation, when compared with a high-solar factor solution (ALU.D_DB; g-value 0.65). The operation phase is the greatest contributor in all scenarios, for all impact categories, accounting for 71-95%.

The office room was also analyzed in the other two climates (Berlin and Larnaca) in order to assess the influence of climate data on the LCA results. The life cycle assessment of window components and processes was performed for the GW impact category, considering different shading strategies (with or without direct sun exposure) for the South orientation. Figure 3.2 presents the GW impacts for the 30-year use of the office room in the three climate zones, comparing all the alternative windows. Three alternative European climate zones were considered: Coimbra (HDD 1304°C, CDD 424°C), Berlin (HDD 3155°C, CDD 170°C), and Larnaca (HDD 759°C, CDD 1260°C).

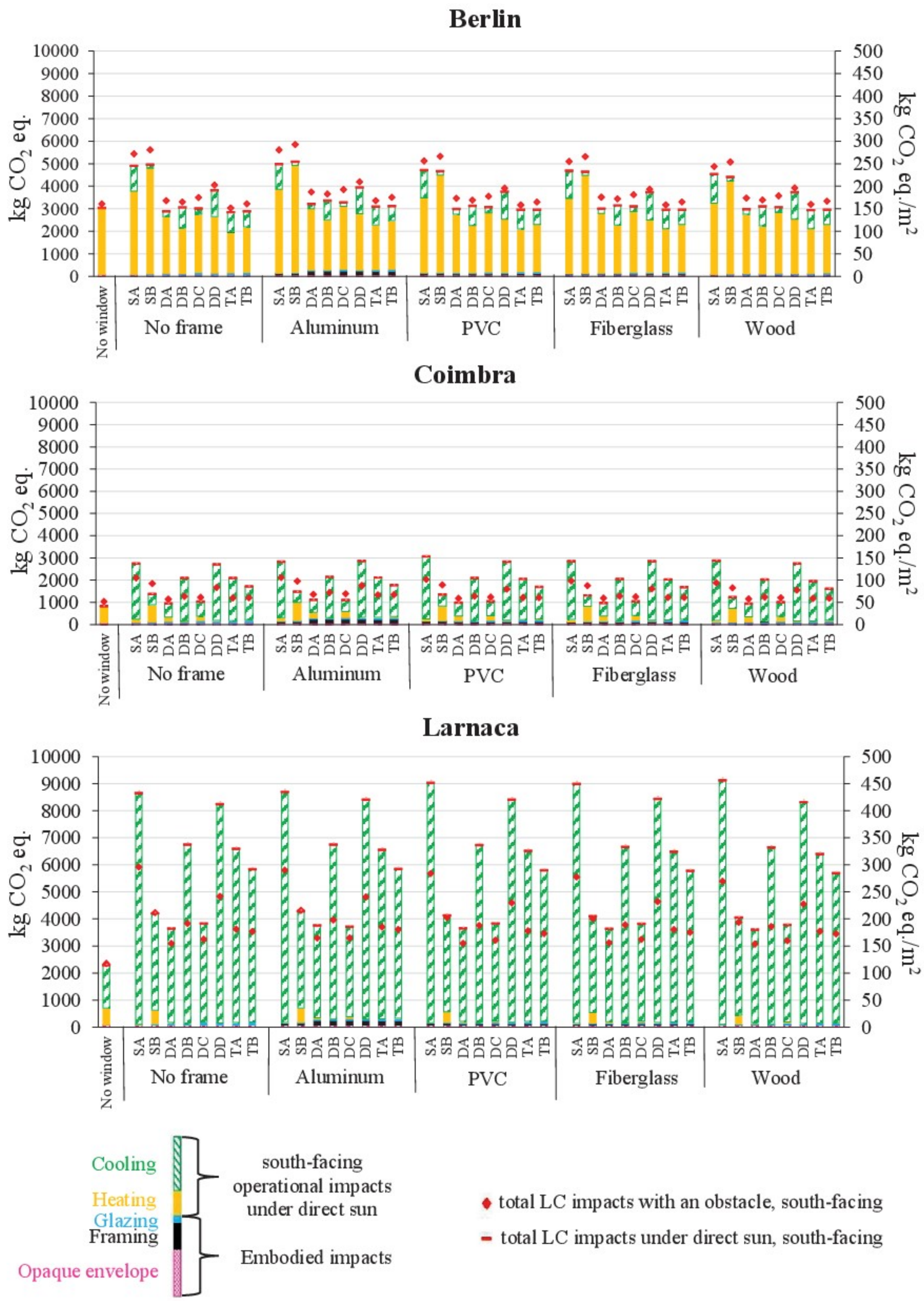


Figure 3.2 Global warming impacts of 30-year use of the office room in three climate zones (Berlin, Coimbra and Larnaca), comparing different windows for South orientation, under direct sun or with an obstacle

The results indicate that the cooling energy needs are dominant in Coimbra and Larnaca. Thus, the window solutions with the lowest solar factor (SB, DA and DC, g-value<0.40) have lower operational impacts in warm climates than the high-solar factor windows (SA, DB, DD). When there is no obstacle, the operational impacts of the low solar factor windows are significantly lower than when there is an obstacle. For example, in Larnaca, a low-solar factor window (ALU.D_DA; g-value 0.33) with direct sun exposure has a 43% lower GW impacts than a high-solar factor solution (ALU.D_DB; g-value 0.65), while if there is an obstacle it has a 16% lower GW impacts.

When comparing the life cycle GW impacts of the 30-year use of the room with different framed windows and direct sun exposure, around 2941 kg CO_2 eq. was estimated as the lowest value in Berlin (for WOO.SDT_TA), 3604 kg CO_2 eq. in Larnaca (for WOO.SDT_DA), and 940 kg CO_2 eq. in Coimbra (by WOO.SDT_DA). If there is an obstacle, the GW impacts of the aforementioned windows were increased by 9% in Berlin and 22% in Coimbra, while it fell by 14% in Larnaca.

3.3.1.1. Validation tests based on EN 15265 (2007)

Table 3.6 presented 12 given test cases with the reference values for annual heating/cooling energies from standard and the calculated results. Finally, the achieved accuracy levels for all tests are specified. The results show that all validation cases passed within accuracy level C.

Table 3.6 The achieved accuracy levels for 12 given test cases based on EN 15265 (2007)

Test case	$Q_{H,ref}$ (kWh)	Q_H (kWh)	$Q_{C,ref}$ (kWh)	Q_C (kWh)	r_{QH}	Accuracy level of Q_H	r_{QC}	Accuracy level of Q_C
Test 1 (reference case)	748.0	829.6	233.8	252.4	0.08	B	0.02	A
Test 2 (as test 1 + change inertia)	722.7	808.5	200.5	225.2	0.09	B	0.03	A
Test 3 (as test 1 + no internal gains)	1368.5	1451.1	43.0	34.6	0.06	B	0.01	A
Test 4 (as test 1 + no solar protection)	567.4	605.9	1530.9	1691.0	0.02	A	0.08	B
Test 5 (as test 1 + intermittent heating & cooling during weekdays from 8 am to 6 pm)	463.1	486.7	201.7	237.4	0.04	A	0.05	A
Test 6 (as test 2 + intermittent heating & cooling as for test 5)	509.8	554.0	185.1	217.9	0.06	B	0.05	A
Test 7 (as test 3 + intermittent heating & cooling as for test 5)	1067.4	1104.5	19.5	20.4	0.03	A	0.00	A
Test 8 (as test 4 + intermittent heating & cooling as for test 5)	313.2	322.6	1133.2	1302.2	0.01	A	0.12	C
Test 9 (as test 5 + external roof)	747.1	809.8	158.3	209.4	0.07	B	0.06	B
Test 10 (as test 6 + external roof)	574.2	552.7	192.4	217.5	0.03	A	0.03	A
Test 11 (as test 7 + external roof)	1395.1	1464.7	14.1	19.0	0.05	A	0.00	A
Test 12 (as test 8 + external roof)	533.5	570.8	928.3	1103.2	0.03	A	0.12	C

3.3.1.2. Verification of the reference room model with a reference building

In this section, thermal performance assessment of the alternative glazing solutions with the various parameters has been carried out in context of a reference office building. Regarding the reference room, the results have been attained in accordance with facing North, East, South and West and then weighting factors based on reference building have been assigned to each orientation as presented in Figure 3.3.

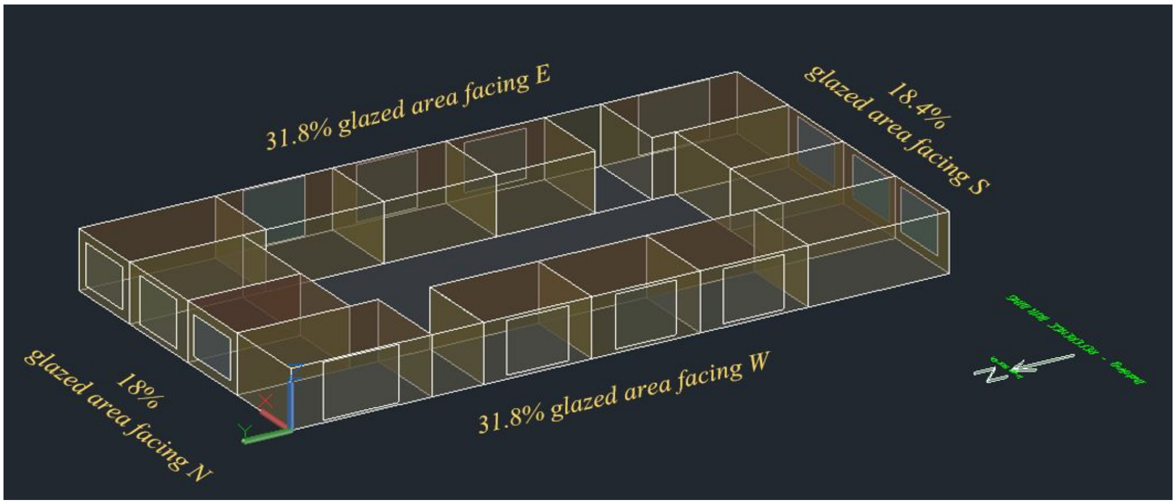


Figure 3.3 Percentage of glazing area related with each orientation for reference building

Table 3.7 presented the results from the reference room after assigning the weighting factors comparing to the reference building in three locations, for the selected scenario: WWR of 0.5, ventilation rate of 0.4 h^{-1}, and one occupant from 8 am to 6 pm in working days.

Table 3.7 The annual energy needs from the reference room after assigning the weighting factors comparing to reference building in three locations (Coimbra, Berlin and Larnaca)

i) Reference room after assigning the weighting factors									
Selected scenario: WWR of 0.5, ventilation rate of 0.4 h^{-1}, and 1 occupant from 8 am to 6 pm in working days									
Coimbra			Berlin			Larnaca			Glazing solutions
Annual energy needs (kWh/m^2)	Heating energy needs (kWh/m^2)	Cooling energy needs (kWh/m^2)	Annual energy needs (kWh/m^2)	Heating energy needs (kWh/m^2)	Cooling energy needs (kWh/m^2)	Annual energy needs (kWh/m^2)	Heating energy needs (kWh/m^2)	Cooling energy needs (kWh/m^2)	
27.48	3.42	24.06	30.87	20.83	10.04	45.32	1.26	44.06	Single A
12.60	7.15	5.46	27.16	25.29	1.87	21.33	3.91	17.42	Single B
10.04	1.01	9.04	11.42	7.85	3.57	18.80	0.19	18.61	Double A
23.70	0.25	23.44	17.18	6.37	10.81	37.24	0.01	37.23	Double B
10.57	1.14	9.43	12.21	8.48	3.73	19.69	0.24	19.46	Double C
26.97	0.92	26.05	22.48	10.77	11.70	43.16	0.12	43.03	Double D
24.34	0.06	24.28	15.98	4.50	11.48	36.99	0.00	36.99	Triple A
20.48	0.23	20.25	14.97	5.74	9.23	32.68	0.01	32.67	Triple B
ii) Reference building									

Selected scenario: WWR of 0.5, ventilation rate of 0.4 h^{-1}, and 1 occupant from 8 am to 6 pm in working days									
Coimbra			Berlin			Larnaca			
Annual energy needs (kWh/m^2)	Heating energy needs (kWh/m^2)	Cooling energy needs (kWh/m^2)	Annual energy needs (kWh/m^2)	Heating energy needs (kWh/m^2)	Cooling energy needs (kWh/m^2)	Annual energy needs (kWh/m^2)	Heating energy needs (kWh/m^2)	Cooling energy needs (kWh/m^2)	Glazing solutions
32.49	4.31	28.18	33.58	21.09	12.48	49.11	2.13	46.98	Single A
15.12	7.81	7.31	28.19	25.47	2.72	22.23	4.48	17.75	Single B
11.22	0.54	10.68	10.92	5.57	5.34	20.58	0.09	20.49	Double A
29.54	0.10	29.44	19.19	4.39	14.80	42.15	0.00	42.14	Double B
13.05	0.69	12.36	11.81	6.32	5.49	21.49	0.13	21.36	Double C
32.40	0.95	31.45	24.78	9.55	15.23	47.89	0.23	47.66	Double D
31.23	0.00	31.22	18.51	2.36	16.15	41.45	0.00	41.45	Triple A
25.95	0.06	25.89	16.59	3.60	12.99	37.17	0.00	37.17	Triple B

Comparing the results for the total energy needs of the reference building and reference room, it can be noticed that both results follow the same pattern. In other words, the order of glazing solutions in terms of low energy consumption in each location follows the same pattern for both case studies. Consequently, the assessment of the behavior of the window solutions within a different building clarifies the reliability of the reference room to select window solutions in various locations.

3.3.2. Life cycle costing

This section first presents the life cycle cost results for the 30-year use of the office room, and afterwards gives the trade-off results between life cycle costing and annual operational energy needs. Figure 3.4 shows the results for the front wall with the alternative windows and different orientations in Coimbra after assessment of the contribution of individual components and processes to the life cycle cost results. The initial investment relates to the costs of the opaque envelope, the glazing and framing solutions, and the operational costs of the heating and cooling energy needs.

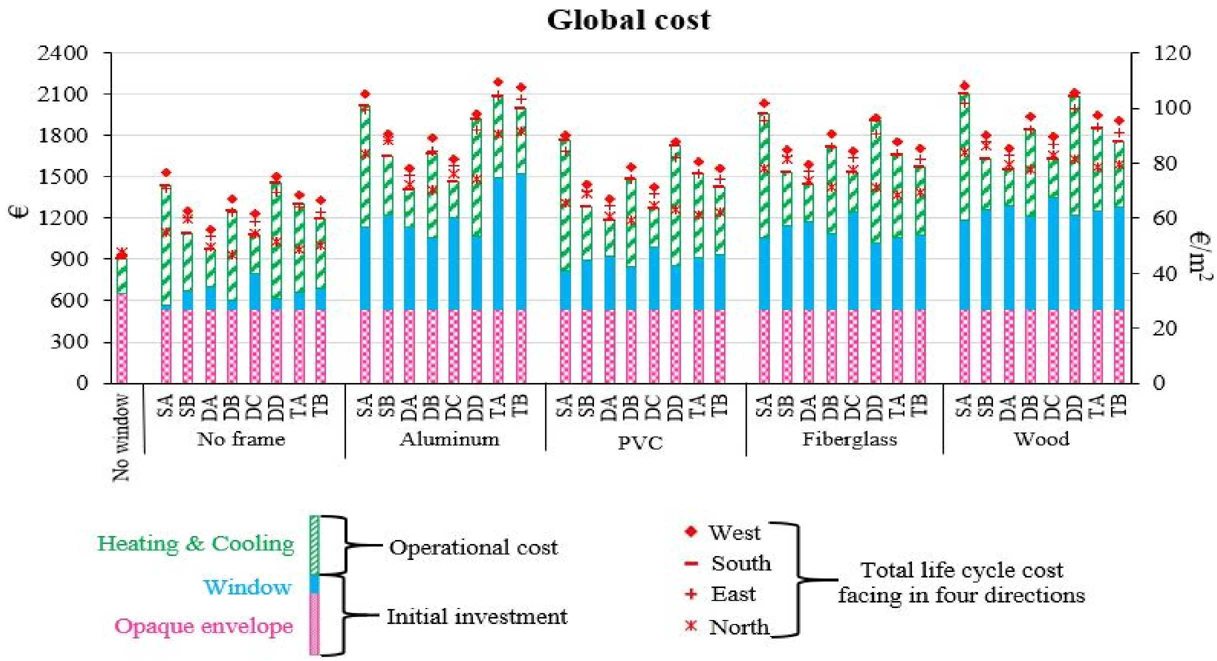


Figure 3.4 Life cycle cost of 30-year use of the office room in Coimbra, comparing different window systems facing in four directions

The results show that the cost-optimal glazing alternative is a double-glazed solution with a solar film since this has the lowest operational impacts. Comparing the framed solutions, we find that the aluminum and wood-framed windows require a higher initial investment cost than the other window alternatives. The PVC-framed windows lead to noticeably lower life cycle costs for all orientations due to the lower initial investment, e.g., 36 to 64% lower life cycle cost than the ALU-framed solutions. For instance, replacing the aluminum frame of the low solar factor window (DA) with the PVC frame leads to a life cycle cost reduction of 18% for the South orientation, or a life cycle cost reduction of 27% by replacing the wood frame of the low-solar factor window (DA) with the PVC frame.

The comparative assessment results for different orientations show that the West orientation for each alternative solution has a higher life cycle cost, owing to the higher operational energy needs. Furthermore, the wall with the triple-glazed solutions and aluminum frame in the West orientation represents the highest life cycle cost (up to about €2186). The lowest life cycle costs were found for the North orientation, except for the lower solar factor solutions (SB, DA and DC). While the lower solar factor solutions for the South orientation resulted in the lowest life cycle costs compared with the other orientations.

Figure 3.5 and Figure 3.6 present the trade-off results for the global cost [€/m^2] and annual operational energy needs [kWh/(m^2.year)] in the three climates, considering South orientation. These figures set out to assess the influence of the solar factor (see Figure 3.5) and the thermal transmittance value (see Figure 3.6) on the operational energy needs and life cycle cost. In Figure 3.5, the size of the points is increased by the higher solar factor, while in Figure 3.6 the size is a function of the thermal transmittance value. The cost-optimal window solutions appear in the lower bound of the life cycle cost, and the energy-efficient solutions in the lower bound of the operational energy needs. As can be seen, the cost-optimal window solutions are represented by the PVC-framed windows for the three climates, due to the lower initial investment of the PVC frames. For Larnaca and Coimbra, the energy-efficient windows are the solutions with the lowest solar factor (DA & DC, g-value<0.40), as can be seen in Figure 3.5 by the accumulation of the smallest points in the lower bound of operational energy needs. The window solutions with the lowest thermal transmittance values are found to be the energy-efficient ones for Berlin (U-value<1.50 W/(m^2K)), as seen in Figure 3.6 from the lower bound of operational energy needs filled with the small-sized points.

A comparison of the two groups of window solutions (cost-optimal and energy-efficient) shows that some solutions are present in both lower bounds. In Coimbra and Larnaca, two low-solar factor solutions (DA and DC, g-value<0.40) with the PVC frame (PVC.D_DA and PVC.D_DC) appear in both lower bounds. In Berlin, the low thermal transmittance solutions (U-value<1.50 W/(m^2K)) with the PVC frame (PVC.T_TA, PVC.T_TB, PVC.D_DA, PVC.D_DC, PVC.D_DB) have the lowest life cycle cost and operational energy needs.

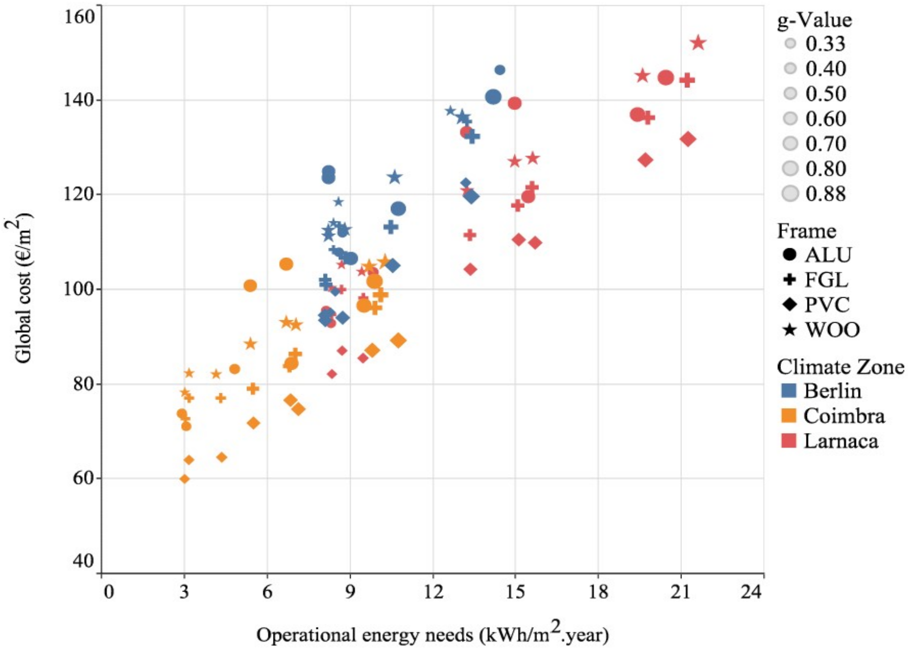


Figure 3.5 Global cost (€/m^2) and annual operational energy (kWh/m^2.year) trade-offs for the office room with alternative windows facing South, comparing three climate regions (Coimbra, Berlin and Larnaca), and assessing the influence of the solar factor

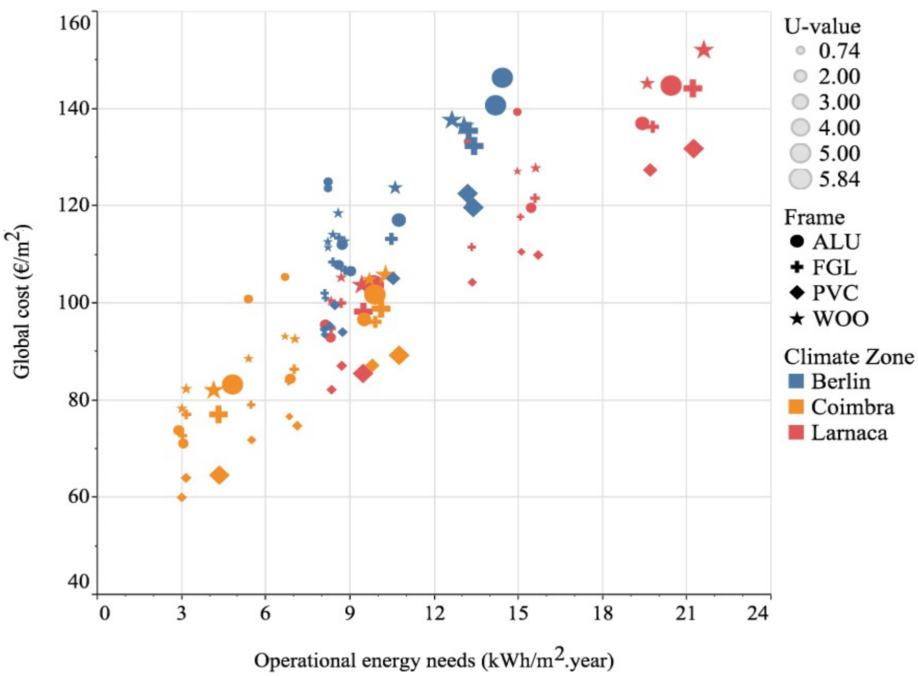


Figure 3.6 Global cost (€/m^2) and annual operational energy (kWh/m^2.year) trade-offs for the office room with alternative windows facing South, comparing three climate regions (Coimbra, Berlin and Larnaca), and assessing the influence of the thermal transmittance value

3.3.3. Pareto optimal window solutions

A trade-off between the environmental and cost LCA has been made for the framed windows, for the five impact categories (NRPE, GW, AC, EU, OD). When considering the trade-offs between the life cycle cost and environmental impacts, the alternative windows in each climate region are dominated by a small number of the window solutions (Pareto optimal solutions).

Figure 3.7 presents all the window solutions and the set of non-dominated window solutions positioned on the Pareto optimal frontiers. It further shows the trade-off between the cost and environmental LCA, for the five environmental impact categories. The Pareto optimal frontier consists of the supported and unsupported non-dominated solutions. In the set of non-dominated window solutions, since the following two solutions are common to all impact categories in Coimbra and Larnaca, they are the supported non-dominated solutions: a solar control double-glazing (DA) with a wood frame (WOO.SDT_DA) and with a PVC frame (PVC.D_DA); and the same is true for two window solutions in Berlin: a low-E coated triple-glazing (TA) with a wood frame (WOO.SDT_TA) and with a PVC frame (PVC.T_TA), except for the eutrophication and ozone layer depletion impact categories.

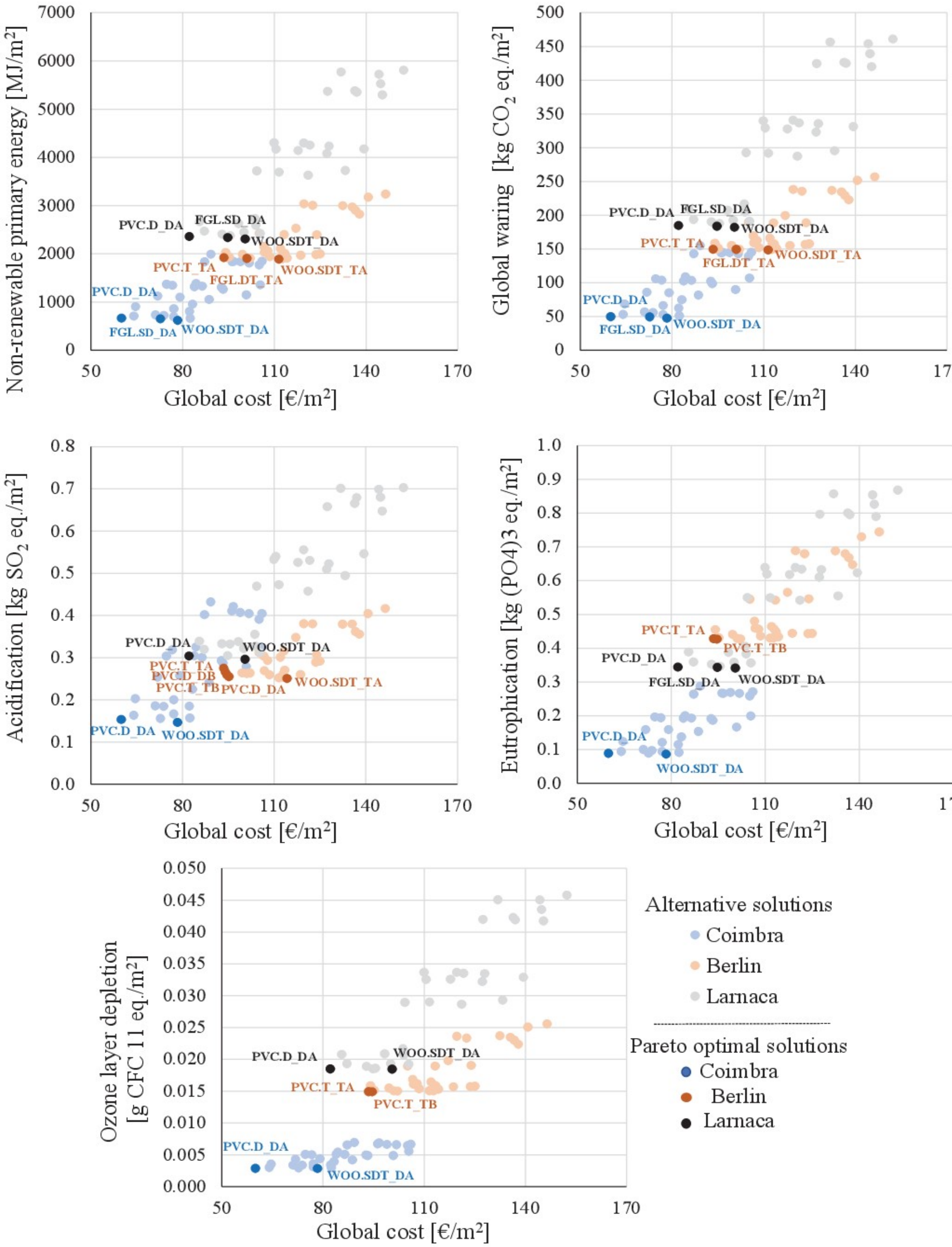


Figure 3.7 The set of non-dominated solutions positioned on the Pareto optimal frontiers for the environmental and cost LCA of the alternative framed windows, in three climate zones: Coimbra, Berlin and Larnaca (South orientation)

A solar control double-glazing (DA) window with a fiberglass frame (FGL.SD_DA) is an unsupported non-dominated solution for the non-renewable primary energy and global warming, in

Coimbra and Larnaca. In Berlin, the unsupported non-dominated solutions vary depending on the selected environmental impact category. Regarding non-renewable primary energy and global warming, the unsupported solution is the window with low-E coated triple-glazing (TA) and a fiberglass frame (FGL.DT_TA). For the ozone layer depletion, eutrophication and acidification, a laminated triple-glazing (TB) window with a PVC frame (PVC.T_TB) is the unsupported non-dominated solution. Regarding acidification, we can find the double-glazing (DA) window with a PVC frame (PVC.D_DA) and the laminated double-glazing (DB) window with a PVC frame (PVC.D_DB).

3.4. Concluding remarks

An integrated cost and environmental life cycle assessment of 32 alternative window solutions for a reference office room has been presented. The 32 alternative windows combined four framing materials (aluminum, PVC, fiberglass, and wood) and eight glazing alternatives (low versus high values for thermal transmittance and solar factors). Four cardinal directions and three distinct European climates (Coimbra, Berlin and Larnaca) were assessed to explore how climate data and orientation influence the economic and environmental performance of the window solutions.

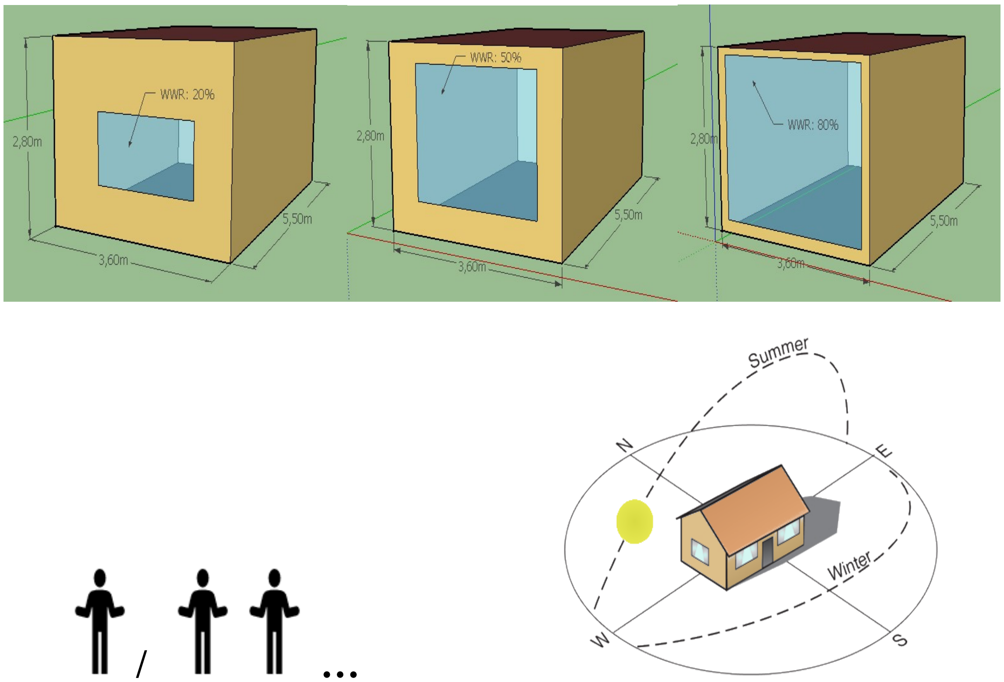
Life cycle impacts were estimated for four environmental categories and non-renewable primary energy showing that glazing is the component with the greatest influence on the total environmental impacts (mainly operational because of heating and cooling energy needs). The impacts are highly dependent on the thermal transmittance values and solar factors; glazing solutions with the lowest solar factor showed lower operational (cooling) impacts in warm climates, and those with the lowest thermal transmittance values had lower operational (heating) impacts in cold climates. Framing options lead to slight differences in the overall impacts, mainly associated with the embodied impacts.

The life cycle cost employed calculated the global costs of the alternative windows and showed that the PVC-framed windows lead to a noticeably lower life cycle costs for all orientations, due to the lower initial investment, e.g., 36 to 64% lower life cycle cost compared with the ALU-framed solutions. The comparative assessment results for different orientations show that the West orientation for each alternative solution involves a higher life cycle cost, owing to the higher operational energy needs. The wall with the triple-glazed window solution and aluminum frame facing West represents the highest life cycle cost (up to about €2186).

Looking at the results, the optimal window solutions that maximize life cycle benefits depend on the climate data and the orientation of the building. A low-solar factor solution is more beneficial in warm climate zones, and low thermal transmittance windows are better in cold climate zones. Even though the frame option does not offer significant operational savings, it can lead to lower embodied impacts. The results of this work have shown that the Pareto optimal window solutions in terms of economic criteria are the PVC-framed windows because of the low initial investment in the PVC frame. The Pareto optimal window solutions for all environmental impact categories in warm climates lead to the low solar factor windows with a PVC or wood frame. For cold climates, the Pareto optimal window solutions are associated with the window solutions with a low thermal transmittance value and with a PVC or wood frame.

The integrated life cycle approach with Pareto bi-objective optimization implemented in this chapter can effectively evaluate the environmental impacts and costs of window solutions and recognize optimum thermal transmittance values and solar factors. The glazing and frame solutions studied in this study cover a large range of the market in terms of thermal transmittance and solar factor. This chapter provides insights into and recommendations for the design of windows solutions by addressing different climatic conditions and window orientations. For future market solutions with values of thermal transmittance and solar factor differing from those presented in this study, new results and conclusions can be obtained by applying the proposed approach. In addition, the limitations of this study could be tackled by future research to address other parameters that affect the environmental and economic performance of windows, such as window area, lighting, occupancy level, and air ventilation rate.

4. Key drivers of life cycle environmental and cost assessment of windows for different European climate zones[3]



Abstract: This chapter presents a comprehensive sensitivity analysis to identify and rank the parameters that contribute the most to the variability in 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 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.

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[3] Based on: Saadatian, S., Rodrigues, C., Freire, F., & Simões, N. (2022). "Key drivers of life-cycle environmental and cost assessment of windows for different European climate zones", Journal of Building Engineering, vol. 50, 104206. https://doi.org/10.1016/j.jobe.2022.104206

4.1. 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 (Zhang et al., 2011; Zhu et al., 2013), but also in the overall energy needs of buildings (Goia, 2016; Mangkuto et al., 2016; Zhu et al., 2013), 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 2ºC (preferably 1.5ºC) by reducing greenhouse gas emissions to pre-industrial levels (UNFCCC, 2015). 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 (Alanne et al., 2007; ALwaer and Clements-Croome, 2010; Grynning et al., 2013). 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 (Heijungs, 1996; Kristensen and Petersen, 2016).

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 (ALwaer and Clements-Croome, 2010; De Koning et al., 2010; Groen et al., 2017; Jonsson and Roos, 2010; Maltais and Gosselin, 2017; Scorpio et al., 2020; Yang et al., 2021). For example, Tavares et al. (2016) 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. (2016) 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 (2017) 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. (2020) 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. (2021) 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 (Rodrigues and Freire, 2021). For example, Tian and De Wilde (2011) 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 (2012) 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. (2008) 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. (2016) 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 (e.g., 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. (2021a), and secondly in terms of life cycle cost and environmental impacts by Saadatian et al. (2021b), 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 (Minne et al., 2015; Su and Zhang, 2010), but disregarding the environmental performance of windows over their entire life cycle. An exception is the work of Salazar (2014) 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 (Ghisi and Tinker, 2005; Lee et al., 2013; Ma et al., 2015; Persson et al., 2006; Phillips et al., 2020). For example, Lee et al. (2013) 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 (2010) have measured the environmental impacts of operational performance of various windows with WWR ranges of 10 to 70% in different orientations, for a typical Chinese office building. Marino et al. (2017) 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 (Wei et al., 2015).

The novelty of this chapter 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 chapter 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.

4.2. 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. This analysis expands on previous LCA work described in Chapter 3, which performed a comprehensive LCA on a limited number of window alternatives with the same area. The present chapter 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 4.1. 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.

4.2.1. 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) (ISO 13791: 2004), 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 Chapter 3. The use of a reference building model allows to easily compare the results with similar studies (Zeferina et al., 2021).

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) and EN 16798-3 (2017). The alternative locations represents different European climate zones according to the Köppen-Geiger classification system (Kottek et al., 2006; Rubel et al., 2017): Portugal (Coimbra) as a temperate climate with Mediterranean hot summer (Csa); Cyprus (Larnaca) as a semi-arid (steppe) desert climate (BSh); and Germany (Berlin) as a temperate oceanic climate (Cfb). Table 4.1 shows the window- and operation-related parameters selected for this analysis.

Table 4.1 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 $W/(m^2K)$), High (U=2.56 $W/(m^2K)$)
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

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 (Spielmann et al., 2007). Technical data of the windows was taken from producers and suppliers, and relevant environmental product declarations (EPDs) presented by Saint-Gobain Glass. 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™ (U.S. Department of Energy, 2019). GenOpt (Berkeley Lab, 2016) 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 (European Union, 2011), 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. (2014). While for Germany and Cyprus, secondary data was based on Ecoinvent v.3.2. database (Moreno Ruiz E., Lévová T., Bourgault G., 2015) due to the lack of specific data for these locations.

4.2.2. 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) and ISO 14044 (2006) standards. Global warming impact category (GW, time horizon of 100 years) calculated using the IPCC method (IPCC Report, 2014) 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 (European Commission, 2012). The average discount rate of 3% was considered representing the current trend in Europe (The World Bank, 2019). 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 (Eurostat, 2019). Additional details are presented in Chapter 3.

4.2.3. Sensitivity analysis method and scenarios definition

The selection of sensitivity analysis methods are based on input data requirements, output type, and calculation time (Bisinella et al., 2016; Groen et al., 2014), as well as data availability and magnitude of data uncertainties (Groen et al., 2017). Global sensitivity analysis have been widely used in LCA studies to quantify the contribution of each input parameter to the output variance (Groen et al., 2017; Wei et al., 2015). Three global sensitivity analysis methods have been commonly used, namely Standardized Regression Coefficient (SRC), Spearman Correlation Coefficient (SCC), and Sobol' indices (Groen et al., 2017; Pacheco-Torgal and Jalali, 2011). For case-studies with small input uncertainties (as the one presented in this article), SRC methods have been identified as having the best performance (Groen et al., 2017). Regression-based methods have also been commonly employed for sensitivity analysis in building performance studies (Ballarini and Corrado, 2012; Breesch and Janssens, 2010; Tian, 2013; Tian and De Wilde, 2011; Yildiz et al., 2012). 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:

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

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

where $\bar{y}$ is the average value of model output, $\bar{x}$ 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 (Tan et al., 2017).

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 4.2a). 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 4.2b) 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 4.2c_1), while for Berlin evaluated the influence of thermal transmittance (Table 4.2c_2). Next, a fourth set of scenarios in Coimbra and Larnaca assessed the influence of U-value (Table 4.2d_1), but the influence of ventilation rate in Berlin (Table 4.2d_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.

Table 4.2 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°C) Berlin (3155°C) Larnaca (759°C)	North East South West		
(b) Second set of scenarios: window-to-wall ratio (36 scenarios)			
Location (HDD)	Window orientation	WWR	
Coimbra (1304°C) Berlin (3155°C) Larnaca (759°C)	North East South West	0.2 0.5 0.8	
(c_1) Third set of scenarios in Coimbra and Larnaca: solar factor (16 scenarios)			
Location (HDD)	Window orientation	WWR	g-value
Coimbra (1304°C)	North	0.2	Low (g=0.35)

Larnaca (759°C)	East South West		High (g=0.78)	

(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°C)	North East South West	0.2	Low (U=0.96) High (U=2.56)

(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°C) Larnaca (759°C)	North East South West	0.2	Low (g=0.35)	Low (U=0.96) High (U=2.56)

(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°C)	North East South West	0.2	Low (U=0.96)	0.4 0.8

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).

4.3. Results and discussion

The standardized regression coefficient (SRC) results for the sequential set of analyses are presented in this section. Section 4.3.1 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 4.3.2 presents the results for the second set of scenarios, after WWR has been selected as the most influential variable. Section 4.3.3 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 for colder climate (Berlin). Section 4.3.4 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.

4.3.1. 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°C), Berlin (3155°C) and Larnaca (759°C).

Figure 4.1 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 variable is the solar factor for warmer climates, while for cold climate is the thermal transmittance value. 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.

	Life cycle global warming impacts											
Location	Coimbra				Berlin				Larnaca			
Orientation	North	East	South	West	North	East	South	West	North	East	South	West
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

Figure 4.1 Standardized regression coefficient (SRC) depicting the relative contribution of each variable in the alteration of total life cycle global warming impacts and total 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.

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.

4.3.2. 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).

Figure 4.2 shows the SRC results depicting the relative contribution of each variable to the total life cycle GW impacts and total 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), while U-value is the most influential in the cold climate (Berlin). Solar factor shows negative correlation in smaller windows (lower WWRs) in North orientation for Berlin, presenting higher influence to life cycle costs than to global warming impacts. Thermal transmittance presents higher influence in bigger windows (higher WWRs) in Berlin, while it presents higher influence in smaller windows (lower WWRs) in warmer locations. 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.

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

Figure 4.2 Standardized regression coefficient (SRC) depicting the relative contribution of each variable in the alteration of total life cycle GW impacts and total 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.

4.3.3. 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 most influential parameter 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): 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^2K)) and high (U=2.56 W/(m^2K)) thermal transmittance value for the four window orientations in Berlin were assessed (8 scenarios).

4.3.3.1. Influence of solar factor in Coimbra and Larnaca

Figure 4.3 shows the SRC results depicting the contribution of each variable to the total 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 on total life cycle global warming impacts and costs in both locations. 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

Figure 4.3 Standardized regression coefficient (SRC) depicting the relative contribution of each variable in the alteration of total life cycle GW impacts and total 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.

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

Figure 4.4 shows the SRC results depicting the contribution of each variable to total 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 total 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.

	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	-0.4	-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

Figure 4.4 Standardized regression coefficient (SRC) depicting the relative contribution of each variable in the alteration of total life cycle GW impacts and total 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.

4.3.4. 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 total life cycle GW impacts and costs in warmer climates, while ventilation rate presented the highest influence in the cold climate. 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).

4.3.4.1. Influence of thermal transmittance value in Coimbra and Larnaca

Figure 4.5 shows the SRC results depicting the contribution of each variable to total 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 total life cycle global warming impacts and costs in both locations. 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.

	North		East		South		West	
Life cycle global warming impacts								
Location: Coimbra								
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

Figure 4.5 Standardized regression coefficient (SRC) depicting the relative contribution of each variable in the alteration of total life cycle GW impacts and total 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.

4.3.4.2. Influence of ventilation rate in Berlin

Figure 4.6 shows the SRC results depicting the contribution of each variable to total 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 total 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).

	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

Figure 4.6 Standardized regression coefficient (SRC) depicting the relative contribution of each variable in the alteration of total life cycle GW impacts and total life cycle costs for alternative ventilation rates and window orientations, with low thermal transmittance solutions (U-value=0.96 W/(m^2K)) 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

4.4. Concluding remarks

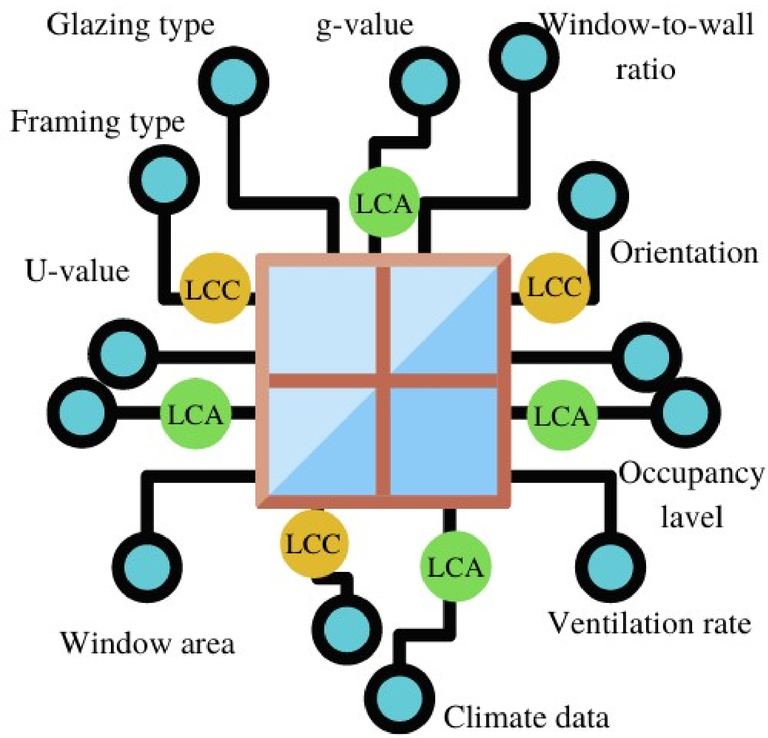
The main goal of this chapter was to perform a sensitivity analysis to identify the key drivers and rank the input parameters which contribute the most to variability of life cycle global warming impacts and costs of windows for three European locations in different climate regions. A set of alternative 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 chapter provides recommendations for the selection of windows to promote lower life cycle global warming impacts 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.

5. Environmental and cost life cycle approach to support selection of windows in early stages of building design[4]



Abstract: This chapter presents an environmental and cost streamlined life cycle assessment (LCA) approach, incorporating probabilistic triage, to support early-decision making for selection of window materials and components. This approach permits also to reduce the uncertainty in the estimated results by means of sequentially specifying attributes based on the attribute ranking. For demonstration purposes, a large number of window alternatives has been assessed for a reference office room. This approach proved to be effective in providing robust results to support the selection of windows by specifying very few window-related attributes (less than 8). The attribute ranking results show that the most influential attributes in terms of cost and environmental LCA are window-to-wall ratio and orientation, respectively. Future market window solutions with a wide range of alternative materials and components, impacting thermal transmittance and solar factor values, can be assessed using this approach to find optimal cost and environmental performance of buildings.

[4] Based on: Saadatian, S., Simões, N., Freire, F. (2021). "Environmental and cost life-cycle approach to support selection of windows in early stages of building design", submitted to Journal of Cleaner Production (Under review).

5.1. Introduction

Window attributes need to be selected at an early-stage of a building design, such as frame and glass options, area, thermal transmittance value, solar factor, and orientation of windows, as they highly influence the environmental and cost performance of buildings (Souviron et al., 2019). However, detailed data inventory is a critical step for life cycle assessment due to the impact on the results. This issue is particularly challenging at early stages of design when specific and reliable data is not available. In addition, LCAs are usually performed at late design stages, when most decisions have already been made and the potential to make changes is low (Meex et al., 2018). The selection of window materials and components with the lowest life cycle impacts and costs in an early-design stage is important to minimize environmental impacts and costs of buildings.

Streamlined LCA can support early-stage design decisions; however, streamlined LCA approaches applied to buildings have been mostly focused on the embodied impact assessment of materials (Asdrubali et al., 2021). Many of these streamlined LCA studies have integrated building information modelling (BIM) with other tools to translate technical drawings into a bill of materials. For example, Schlueter and Thesseling (2009) have used a BIM model to estimate the required data and parameters during the design stage, coupled with another tool enabling the estimation of the energy needs for the design varieties. Other streamlined LCA studies have used a macro component approach to identify a range of presumed construction solutions for the key components of a building, incorporating life cycle embodied data (Bribián et al., 2011; Gervásio et al., 2014; Pushkar et al., 2005). In general, these streamlined LCA approaches simplify the assessment of the life cycle environmental performance of a building with limited data, as well as supports decision-making for the use of alternative construction solutions aiming to reduce energy consumption and life cycle impacts. However, none of the just mentioned streamlined LCA approaches has focused on windows.

It should be underlined that streamlined LCA approaches applied at early design stages of buildings have to deal with many uncertainties due to the lack of detailed information about quantities and types of materials and activities (Galimshina et al., 2020). Streamlined LCA leads with several issues particularly concerning the robustness of the results: whether there is too much uncertainty and variation in the attribute specification, and how detailed the attributes need to be provided by the designer. Hence, it is essential to support the confidence in the results estimated by a streamlined LCA approach. These approaches have rarely addressed the uncertainty caused by the limited information at early design processes. Two exceptions are the separate works of Basbagill et al. (2013) and Rodrigues et al. (2018). Basbagill et al. (2013) presented a novel approach to estimate building embodied impacts based on different amounts of information addressing uncertainty. Sensitivity analysis was conducted on the embodied impacts of a range of building shapes and design parameters. The distribution of embodied impacts among building parameters was shown by an impact allocation scheme, and material and thickness alternatives with the greatest embodied impact reductions were presented by an impact reduction scheme. Rodrigues et al. (2018) that developed a streamlined cost and environmental LCA approach to building retrofits, including uncertainty analysis to tackle the lack of information at early design processes by using the building attribute to impact algorithm approach, which includes structured under-specification and probabilistic triage.

The impact of windows in a building is highly associated to its energy behavior. To estimate the influence of windows on the energy performance of buildings at early design stages, there are energy modeling software packages helping practitioners comparing the performance of window alternatives; however, these tools regularly need detailed information that is only accessible after the building design has been completed. Another limitation for window energy modeling is that it is time consuming. COMFEN is one of the window energy modeling tools to simulate the influence of window variables on energy consumption, thermal and visual comfort. However, designers implementing COMFEN encounter multiple design configurations forcing them running numerous simulations which is extensively costly and time-consuming. Garg et al. (2014) developed a tool for optimizing the window configuration (WinOpt) by computing the energy consumed by the building using EnergyPlus and then optimizing the user-selected parameters by GenOpt. This tool can therefore be useful in reducing the time and cost to assess operational energy performances, yet a streamlined environmental and cost life cycle approach of alternative window solutions is lacking (Baldinelli et al., 2014). Tools are still required for providing advice on the selection of window attributes at early stages of a building design in order to have the greatest impact on the cost and environmental performance.

Windows face different types of decisions at early design stages of buildings, such as which window-to-wall ratio is appropriate for each building space, or which window properties are more appropriated regarding the particular orientation and climate data. A streamlined LCA is lacking to perform an integrated environmental and cost assessment of windows, which fully integrate embodied and operational energy assessment of windows at early stages of a building design.

The main goal of this chapter is to present a streamlined environmental and cost LCA approach, incorporating probabilistic triage, to support the selection of windows in early-design stages of buildings This approach aims to assess the cost and environmental performance of window solutions with different levels of information specified, as well as reduce the uncertainty in the estimated results by means of sequentially specifying attributes based on a quantified attribute ranking. In addition, this chapter investigates the consistency of the results presented by this probabilistic approach with a full LCA results (defined here as an LCA performed at late design stages of building design) using a reference office room located in Portugal that was previously presented in Chapter 3. This study comprises a set of glazing and frame solutions covering a large range of thermal transmittance and solar factors. Hence, this approach can be further used to perform an environmental and cost LCA of future market window solutions with a wide range of values of thermal transmittance and solar factor.

5.2. Materials and methods

5.2.1. Streamlined environmental and cost LCA approach

An integrated cost and environmental streamlined LCA approach have been developed to rapidly compare the impacts of alternative windows at an early stage of a building design in order to guide the selection of the most affordable and environmentally friendly options. It was developed based on the Building Attribute to Impact Algorithm (BAIA) approach developed by Hester et al. (2018). BAIA is a streamlined LCA method that used a set of attribute-to-activity models (i.e. embodied, operational and cost models) (Hester et al., 2018; Rodrigues et al., 2018) for the inventory analysis, structured under-specification and probabilistic triage. This methodology was adapted to support window selection in a building design process, detailing window- and energy-related information in order to perform an environmental and cost LCA of windows. It was implemented in a Microsoft Excel spreadsheet enabling Monte Carlo simulations for the probabilistic triage assessment.

Figure 5.1 shows the general steps and iterative process for developing the streamlined LCA approach incorporating probabilistic triage. The iterative process starts by characterizing the attributes with their options needed to assess the windows performance in terms of environmental and cost impacts (Step 1). Based on the level of information available (from unspecified to fully specified), various levels of specification can be defined for each attribute (Rodrigues et al., 2018). Step 2 is the implementation of attribute-to-activity models for the costs, embodied and operational energy of windows to transform attributes information into a bill of materials and activities (Hester et al., 2018). Then, environmental and cost LCA are performed using the embodied, operational and cost attribute-to-activity models (Step 3), described in section 5.2.3. Finally, the model estimates the distribution of outcomes by using Monte Carlo simulation (Step 4). Based on the results, two alternative paths can be pursued. If there is sufficient resolution (low standard deviation - SD), a robust decision can be made about a single window, or alternative windows, using a comparison indicator (Huijbregts et al., 2003; Noshadravan et al., 2013; Rodrigues et al., 2018). A comparison indicator characterizes the differences in the cost and environmental impacts of two alternative windows.

If there is insufficient resolution (high SD), the data can be refined and further information can be added according to the attribute ranking in the sensitivity analysis (Step 5 and 6, described in detail in section 5.2.5). The process is iterative until the uncertainty level is adequately reduced and a robust decision can be made.

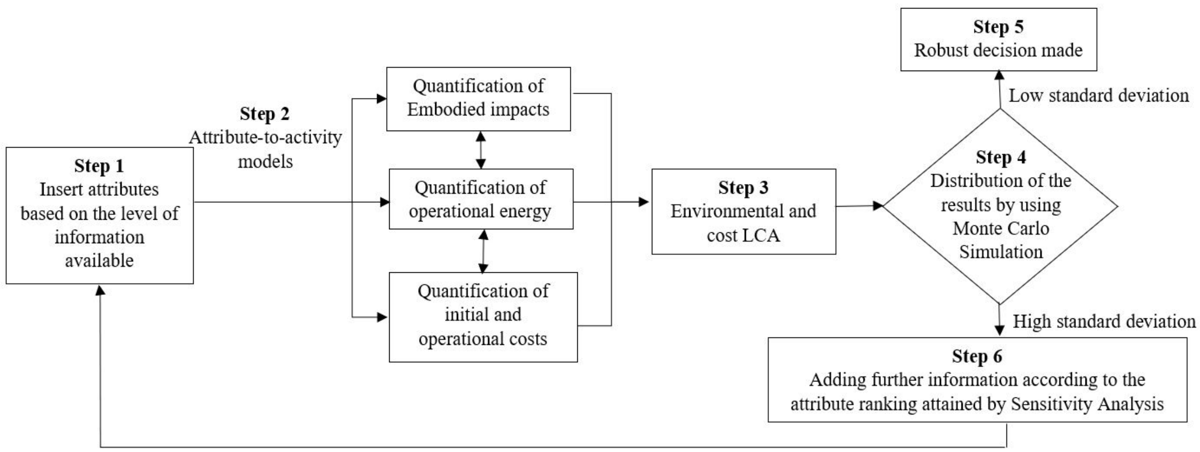


Figure 5.1 General steps and iterative process of the approach to evaluate the environmental and cost life cycle analysis of windows at early-design stage of a building design

5.2.2. Application of the approach for a reference office room

5.2.2.1. Scope definition and window attributes

A life cycle model and inventory has been developed for a large number of window solutions based on previous work presented in Chapter 3 (Saadatian et al., 2021b). A large number of window solutions has been characterized combining several frames and glazing types and other attributes which are listed in Table 5.1 with their options. A specific range of values for window characteristics and dimensions (thermal transmittance, solar factor, window-to-wall ratio (WWR)) has been defined based on market availability. The occupancy range has been selected based on the minimum and maximum number of occupants who can occupy an office room with about 20 m^2, and ventilation rate values according to EN 15251 (2007) and EN 16798-3 (2017) for single office areas.

Table 5.1 List of attributes with their options

Attributes	Unit	Description/Options	Min	Max
Orientation	°	Orientation of the wall with window solution (North axis angle: the angle of the entire building compared to true North)	0	359
WWR	%	Window-to-wall ratio	20	80
Glazing type	-	Single, Double, Triple	-	-
Framing material	-	aluminum, PVC, fiberglass, wood	-	-
Window U-value	$W/(m^2K)$	Thermal transmittance value	0.74	5.84
Window g-value	-	Solar factor	0.33	0.88
Number of occupants	-	Number of occupants in working hours	0	2
Ventilation rate	h^{-1}	volumetric flow rate of outside air into the building	0.4	0.8

For demonstration purposes, a reference office room (5.50 m × 3.60 m × 2.80 m) (as described in ISO 13791: 2004), located in Portugal (Coimbra: heating degree days 1304°C, cooling degree days 424°C) have been studied considering a wide range of alternative windows. The functional unit selected is the reference office area (19.8 m^2) over a period of 30 years. The life cycle model includes the construction phase of the exterior wall where the alternative windows are located, and operation phase (heating and cooling energy use). Technical data of the windows was gathered from producers and suppliers, as well as relevant environmental product declarations (EPDs) (Saint-Gobain Glass, 2019). Secondary data for the Portuguese electricity mix was based on Garcia et al. (2014) and Kabayo et al. (2019). Model and inventory details are based on previous work presented in Chapter 2 (Saadatian et al., 2021a).

5.2.2.2. Inventory analysis – structured under-specification database

A structured under specification approach was used to classify the existing information at the early-design stage of a building (Olivetti et al., 2013). In different levels of specification (from unspecified L1 to fully specified L5), a variety of possible values or alternatives was presented related to each attribute. The structured under specification lets each attribute to be fully specified (e.g., double glazing U=1 $W/(m^2K)$, g=0.33) or ambiguously as a cluster (e.g., glazing), depending on the available information at the early-stage design of the building. Table 5.2 shows an example for the structured under specification model for glazing type. The other structured under specification models are presented in Appendix III.

Table 5.2 The structured under specification model for glazing type

L1	L2	L3	L4 (W/(m^{2}K))	L5 (specified U (W/(m^{2}K)) and g-value)
Glazing	Single-glazed	High g-value (>0.40)	U >5.6	Single A (U=5.8, g=0.88)
		Low g-value (=<0.40)	U ≤5.6	Single B (U=5.6, g=0.39)
	Double-glazed	Low g-value (=<0.40)	U ≤1.1	Double A (U=1.0, g=0.33)
			U >1.1	Double C (U=1.2, g=0.35)
		High g-value (>0.40)	U ≤1.1	Double B (U=1.1, g=0.65)
			U >1.1	Double D (U=2.6, g=0.78)
	Triple-glazed	Low g-value (=<0.40)	U≤0.6	Triple A (U=0.5, g=0.62)
		High g-value (>0.40)	U >0.6	Triple B (U=0.8, g=0.58)

5.2.2.3. Attribute to activity modelling (Step 2)

An attribute to activity modelling estimates the bill of materials and activities by mapping the design attributes (Rodrigues et al., 2018). The following sub-sections present the embodied, operational energy, and cost attribute to activity models.

Embodied attribute-to-activity models

The embodied attribute-to-activity model simplifies the primary information that is normally required to perform a comprehensive LCA to transform attributes into a bill of materials. According to the geometry data of the building, the amount of materials has been calculated using geometric formulas. Data uncertainties are related with the level of specification of the attributes. High uncertainty is caused by the lack of detailed information about material properties, especially in early-design stage of the building. A probability distribution function (uniform) was defined for each attribute (listed in Table 5.1) based on the level of specification within the range of quantities formerly specified for that attribute. A value for each attribute is then randomly selected. Once window solutions are determined from the randomly sampled attributes, the Monte Carlo simulation is performed to estimate the uncertainty range (each iteration runs a set of a 1000 samples).

The mass of materials of the sampled solutions is calculated from the selected window area (based on the window-to-wall ratio). The aggregated masses in each Monte Carlo trial comprise the total window material inventory for that trial. The mass of each material is later multiplied by environmental impact factor presented in Chapter 2 (Saadatian et al., 2021a), for each life cycle stage (from raw material extraction and transport to the production site, production of the materials and transport to the building site).

Operational attribute-to-activity model

The operational attribute-to-activity model incorporates heating and cooling energy metamodels, allowing a rapid estimation of heating and cooling energy use from the randomly sampled windows in each Monte Carlo trial. A stepwise linear regression analysis was applied to build the metamodels. Firstly, the stepwise regression analysis selected which attributes provide a good fit for the model. The data used to create the metamodels was obtained from a thermal dynamic simulation software EnergyPlus™ (U.S. Department of Energy, 2019). The scope of metamodels is generally limited by the dataset used to build it, so these metamodels are limited to Portuguese office buildings, with attributes within the ranges presented in Table 5.1. The interior seasonal heating and cooling setpoints were fixed at 20 °C and 25 °C, respectively. 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 in accordance with energy efficiency class A (European Union, 2011), respectively.

The random simulations were performed for all alternative windows. The stepwise linear regression models for heating and cooling needs in Portugal are illustrated in Figure 5.2.

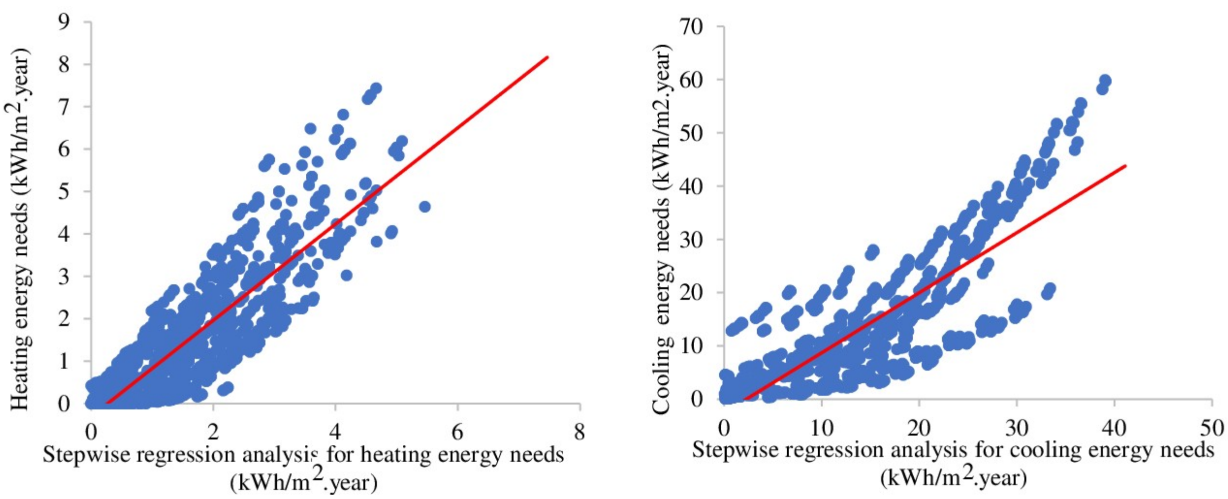


Figure 5.2 Stepwise regression models for heating and cooling energy needs

Operational energy impacts are calculated by multiplying each energy usage output (from the cooling and heating metamodels) with the impact factor for electricity for Portugal based on Garcia et al. (2014) and Kabayo et al. (2019).

Cost attribute-to-activity model

The embodied bill of materials is automatically converted into initial investment costs. All window materials have an associated cost per unit which has been presented in Chapter 3. Once a randomly sampled window is generated, the specific materials are selected, and the cost of materials per unit are multiplied by the quantity of material based on the selected window area, devolving the initial investment costs.

The operational energy costs (heating and cooling) are estimated by multiplying the outputs from heating and cooling energy needs, calculated as described in previous section (in kWh/year), for a lifespan of 30 years, and energy price for Portugal (0.229 €/kWh).

The cost attribute-to-activity model has been characterized by the life cycle cost method, addressing the relevant costs: construction costs (initial investment for the wall and alternative windows), and operational energy costs for heating and cooling.

5.2.3. Environmental and cost LCA (Step 3)

LCA identifies and quantifies the emissions released to the environment and consists of four phases: a) goal and scope definition, b) life cycle inventory (LCI), c) life cycle impact assessment (LCIA), and d) interpretation described in ISO 14040 (2006) and ISO 14044 (2006). In this chapter, only Global Warming (GW) was selected (for its relevance and also for demonstration purposes) for the LCIA. Characterization factors, for a time horizon of 100 years, from the Intergovernmental Panel on Climate Change (IPCC Report, 2014) have been used to calculate GW. The relevance of GW as a key performance indicator is in line with various international agreements, and, more recently, the Paris Agreement commitment to achieve carbon neutrality. However, the approach developed also enables users to calculate other environmental impact categories. SimaPro software has been used for the environmental LCA model and calculations.

As described before, the life cycle cost method has been performed to address the construction costs (initial investment for the wall and alternative windows), and operational energy costs (heating and cooling) using global cost calculation in terms of net present value (European Commission, 2012). Global cost was measured based on the present value of the initial investment costs and operation costs, according to the Commission Delegated Regulation (EU) No 244 (European Commission, 2012). The average discount rate of 3% was assumed based on the current trend in Europe (The World Bank, 2019). The initial investment costs for the window solutions were taken from manufactures and suppliers, and the electricity costs from the European electricity price statistics (Eurostat, 2019).

5.2.4. Sensitivity analysis - attribute ranking

The sensitivity analysis was performed by calculating the Standardized Regression Coefficient (SRC) in order to rank the influential attributes of the environmental and cost LCA of windows. This sensitivity analysis metric has been commonly used in building performance studies (Ballarini and Corrado, 2012; Breesch and Janssens, 2010; Tian, 2013; Tian and De Wilde, 2011; Yildiz et al., 2012). The implemented approach is in line with other studies in the literature (Eisazadeh and Allacker, 2018; Mangkuto et al., 2016; Saadatian et al., 2022; Su and Zhang, 2010). The correlation between model output (global warming impact and global cost) and input parameters (attributes) can be estimated using the following equation:

$$SRC(x_i) = a_i.(S_{x_i}/S_y) \tag{4}$$

where S_y is the standard deviation of the output, S_{xi} is the standard deviation of the i^{th} attribute, a_i is the estimated regression coefficient for the i^{th} attribute, and SRC (x_i) is the standardized regression coefficient of the i^{th} attribute.

SRC can be employed as a sensitivity index to measure the influence of altering each attribute from its mean by a fixed fraction of its standard deviation, whereas the values of the other attributes consider fixed values. In addition, a higher absolute SRC value shows the sensitivity level of the model output to the specific attribute (Tan et al., 2017). SRC values range from -1 to 1, to enable the identification of the key attribute with the highest influence on the environmental and cost performance of windows. Positive correlation coefficients confirm that a growth of an attribute will consequence an increase of cost and environmental LCA result, and negative correlation coefficients means the opposite, a decrease of cost and environmental LCA result.

5.2.5. Evaluation of the results (Step 4, 5 and 6)

The distribution of the results is calculated using Monte Carlo simulation (Step 4). Based on the level of resolution (standard deviation - SD), two alternative paths can be pursued:

1. If there is sufficient resolution (low standard deviation), a robust decision can be made about a single window, or alternative windows (using a comparison indicator) (Huijbregts et al., 2003; Noshadravan et al., 2013; Rodrigues et al., 2018). The cost and environmental performance results of two alternative window solutions were compared using a comparison indicator (Step 5). A comparison indicator represents the difference in the cost and environmental impacts of two alternative windows.

2. If there is insufficient resolution, a sensitivity analysis is performed and further information can be included in the model based on the attribute ranking. Following that, the attributes can be added sequentially based on the attributes' influence on the results (attribute ranking), until an acceptable SD is achieved (Hester et al., 2017). The results will then indicate how many specified attributes are needed to support a robust decision in an early-design stage of a building (Step 5).

5.3. Results and discussion

The streamlined LCA approach has been employed to support the decision-making process regarding the selection of windows for office use in the Portuguese context, in terms of cost and environmental performances. To assess the robustness and effectiveness of this approach, section 5.3.1 presents a comparison between the results achieved from the streamlined LCA approach and a full LCA results presented in Chapter 3. The comparison aimed at investigating whether the results obtained using a full LCA model (Chapter 3) appear within the range of the results using the streamlined LCA model. Section 5.3.2 presents the results of a comparative analysis using a comparison indicator. Finally, section 5.3.3 presents the results from a sequential specification of attributes based on attributes ranking using the standard regression coefficient (SRC).

5.3.1. Comparison of results with a full LCA approach

To assess the robustness and effectiveness of the streamlined approach, two validation strategies have been implemented with different levels of specification. In the streamlined model, the attributes have been characterized by level of specification depending on the information available. For the first validation strategy (depicted in Figure 5.3), two attributes have been characterized with the 4th level of specification (thermal transmittance and solar factor) and the other attributes with the 1st level of specification (fully unspecified) (according to the structured under-specification classification presented in the Supplementary Material). For the second validation strategy (shown in Figure 5.4), all attributes have been characterized with the 2nd level of specification. The streamlined results are presented in box plots to characterize the upper and lower values, the 25th percentile, the 50th percentile (median) and the 75th percentile. The comparison intended to investigate whether the results presented by the full LCA model presented in Chapter 3 (Saadatian et al., 2021b) appear within the range of the results by the streamlined model (box plots). The streamlined LCA model is considered effective when the results from the full LCA falls within the range of results from the streamlined LCA. For demonstration purposes, each validation strategy compares the results using the streamlined approach with two window solutions, assessed using a full LCA approach, selected from Chapter 3 in order to increase the robustness of the analysis.

The selected window solutions for the first validation strategy (Figure 5.3) are: 1) a window solution characterized by a WWR of 0.2 combining double glazing (U=1.1 W/(m^2K), g=0.65) with PVC frame, facing South (shown with red solid lines); and 2) a window solution characterized by a WWR of 0.5 combining double glazing (U=1.1 W/(m^2K), g=0.65) with Aluminum frame, facing West (shown with red dashed lines). It is assumed 1 occupant and ventilation rate of 0.4 h^{-1} for both window solutions. For the streamlined LCA model (shown in box plots), all attributes have been defined with the 1st level of specification except for the thermal transmittance and solar factor with the 4th level of specification (L4: 1.00 W/(m^2K)<U<1.35 W/(m^2K); L4: 0.60<g<0.65).

Figure 5.3 also specifies that the results from the full LCA (red markers) appear within the range of the results from the streamlined model (box plots), regarding embodied (glazing and framing), and operational (heating and cooling) GW impacts, as well as life cycle costs (investment and operational cost). It can be concluded that the model can provide robust results as decreasing the number of fully specified attributes would just provide a wider range of results.

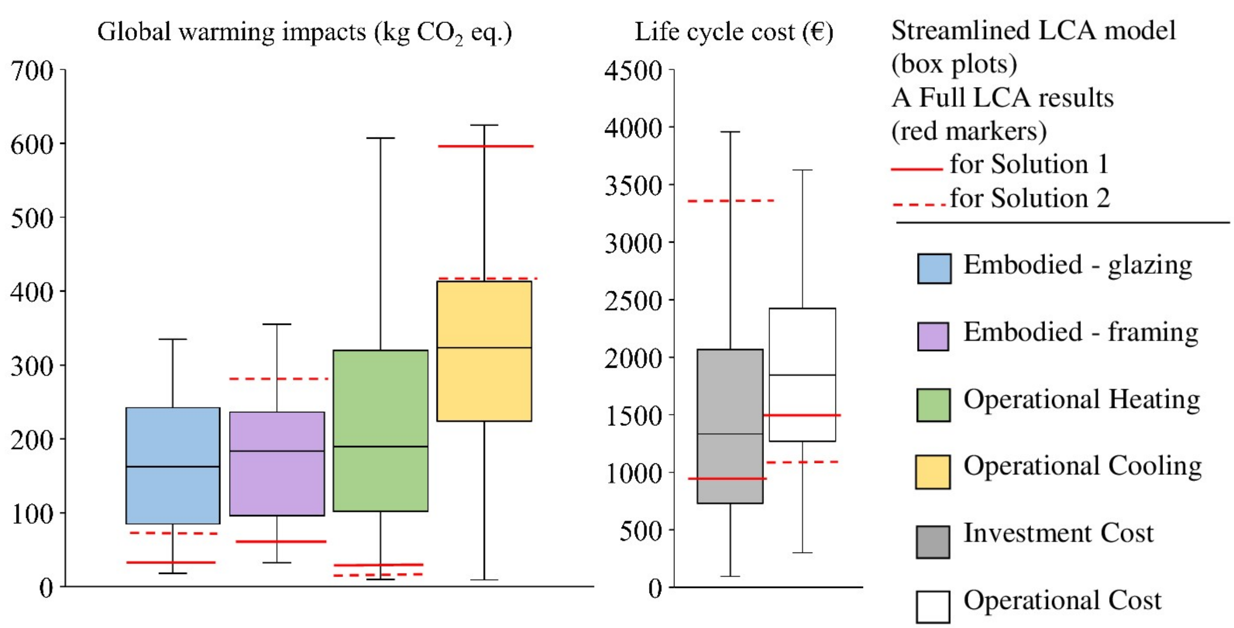


Figure 5.3 Streamlined LCA model (with all attributes characterized with the 1st level of specification, except thermal transmittance and solar factor with the 4th level) vs. a full LCA results (Chapter 3) for the embodied (glazing and framing) and operational energy (heating and cooling) in terms of global warming impacts and costs. Solution 1: a combination of a glazing alternative (double glazing U=1.1 W/(m^2K), g=0.65) and framing option (PVC), WWR of 0.2 facing South. Solution 2: a combination of a glazing alternative (double glazing U=1.1 W/(m^2K), g=0.65) and framing option (Aluminum), WWR of 0.5 facing West

The selected window solutions for the second validation strategy (Figure 5.4) are: 1) a window solution characterized by a WWR of 0.2 combining double glazing (U=1.1 W/(m^2K), g=0.65) and a PVC frame, facing South (shown with red solid lines); and 2) a window solution is characterized by a WWR of 0.5

combining double glazing (U=2.6 W/(m^{2}K), g=0.78) and a PVC frame facing West (shown with red dashed lines). It is assumed 1 occupant and ventilation rate of 0.4 h^{-1} for both window solutions. For the streamlined LCA model, all attributes have been characterized with the 2nd level of specification (shown in box plots) (L2: 0°≤Orientation≤180°; 0.2≤WWR≤0.5; PVC frame; double-glazing; 0.74≤U≤3.30; 0.61≤g≤0.88; with occupancy; 0.40≤ventilation rate≤0.60).

Figure 5.4 indicates that the results from the full LCA (red markers) appear within the range of the results from the streamlined model (box plots), regarding embodied (glazing and framing), and operational (heating and cooling) GW impacts, as well as life cycle costs (investment and operational cost).

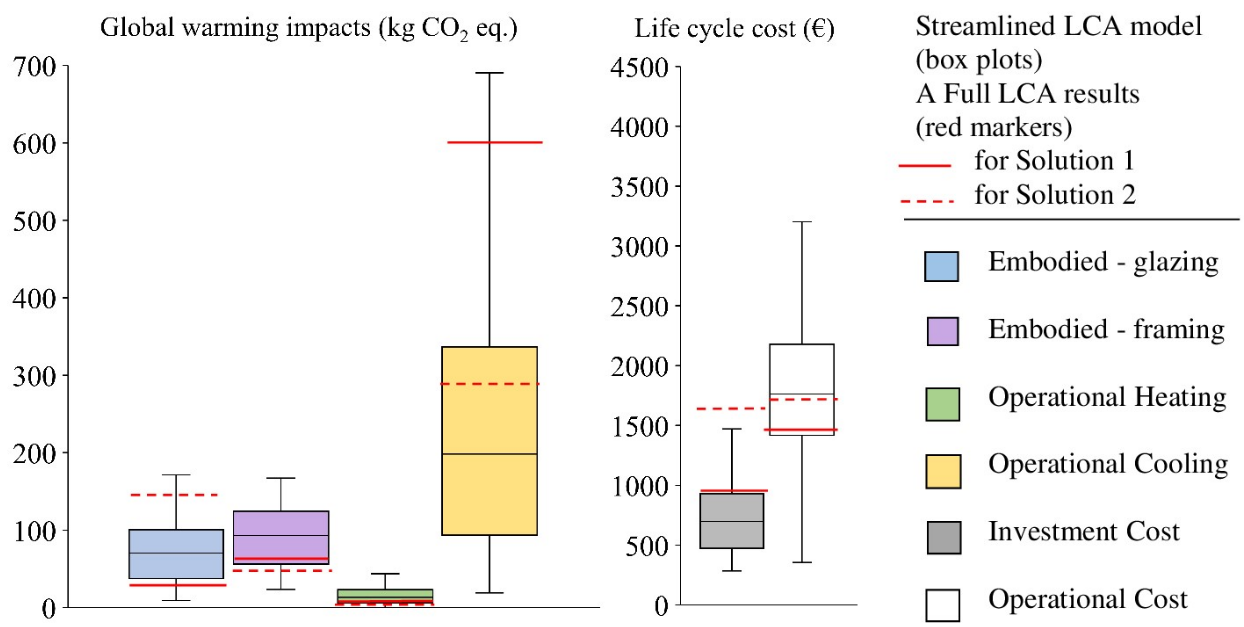


Figure 5.4 Streamlined LCA model (with all attributes characterized with the 2nd level of specification) vs. a full LCA results (Chapter 3) for the embodied (glazing and framing) and operational energy (heating and cooling) in terms of global warming impacts and costs. Solution 1: a combination of a glazing alternative (double glazing U=1.1 W/(m^{2}K), g=0.65) and framing option (PVC), WWR of 0.2 facing South. Solution 2: a combination of a glazing alternative (double glazing U=2.6 W/(m^{2}K), g=0.78) and framing option (PVC), WWR of 0.5 facing West

It can be concluded that that even with lower uncertainty the full LCA still fall within the range of the streamline ones

5.3.2. Comparison of two window solutions using a comparison indicator

This subsection presents the cost and environmental LCA results of two alternative window solutions calculated by the streamlined approach using a comparison indicator (Huijbregts et al., 2003; Noshadravan et al., 2013; Rodrigues et al., 2018). Then, the conclusion has been compared with the cost and environmental LCA results of these two window solutions estimated by a full LCA.

For this purpose, two window solutions have been selected from Chapter 3 for the comparative assessment: 1) a window solution characterized by a WWR of 0.2 combining a double-glazing (Double A: U=1.1 W/(m^2K), g=0.65) and a PVC frame, facing South; 2) a window solution characterized by a WWR of 0.5 combining a double glazing (Double D: U=2.6 W/(m^2K), g=0.78) and a PVC frame facing West. It is assumed 1 occupant and ventilation rate of 0.4 h^{-1} for both window solutions. For the streamlined model, the attributes listed in Table 5.1 have been defined as fully unspecified (1st level of information available), except the glazing type which is fully specified (two double-glazed solutions: Double B and Double D specified by L5, as shown in Table 5.2). Next, the bill of materials and costs, and the energy needs (heating and cooling) have been estimated by the streamlined LCA model. These solutions have been compared to investigate if the comparison results correspond to the ones achieved by the full LCA; and if it is possible to provide valuable conclusions with less input information than a full LCA model.

In order to compare the cost and environmental performances of the alternative window solutions, a comparison indicator (CI) (Gregory et al., 2016; Noshadravan et al., 2013; Rodrigues et al., 2018) has been employed. The application of the comparison indicator in this study aimed at showing the variation in the life cycle cost and environmental impacts of the alternative window solutions, considering the uncertainty and relationship between the compared results. In addition, CI defines the confidence level that one window solution is better than the other one. In this study, the CI has been characterized as the ratio between the global warming (GW) impacts of the two window solutions. The frequency of the CI values less than 1, has been characterized by *f*, as follows:

$$f = P\,(CI < 1) = P\,(\,GW_1\,/GW_2\,) < 1 \qquad (5)$$

It has been assumed that a comparison is considerable when *f* is equal or greater than 0.85 (Rodrigues et al., 2018). It implies the confidence level that solution 1 is better than 2, or 85% of the times the solution 1 is better than 2. CI illustrates the probability that the solution 1 has lower GW impacts than solution 2. On the other hand, 1-*f* indicates the probability that solution 2 has lower GW impact than solution 1.

Figure 5.5 shows the global warming impact results for the two window solutions when only one attribute (i.e. glazing type: Double B vs. Double D) is specified and then when with seven attributes specified (WWR, orientation, thermal transmittance value, solar factor, ventilation rate, number of occupants, and framing material).

Furthermore, Figure 5.5 displays a right plot for the evolution of SD (red dots) and *f* (blue dots) from one to eight specified attributes. These plots reveal the increase of the accuracy of the results by further specifying additional attributes. As can be seen, the SD regarding one specified attribute is much higher than the eight specified ones. However, Figure 5.5 shows that the specification of six attributes is enough to achieve a robust decision f (>=0.85). So, the model effectively recognizes the window solution with the lower GW impacts (Double B), as previously shown in Chapter 3 using a full LCA model.

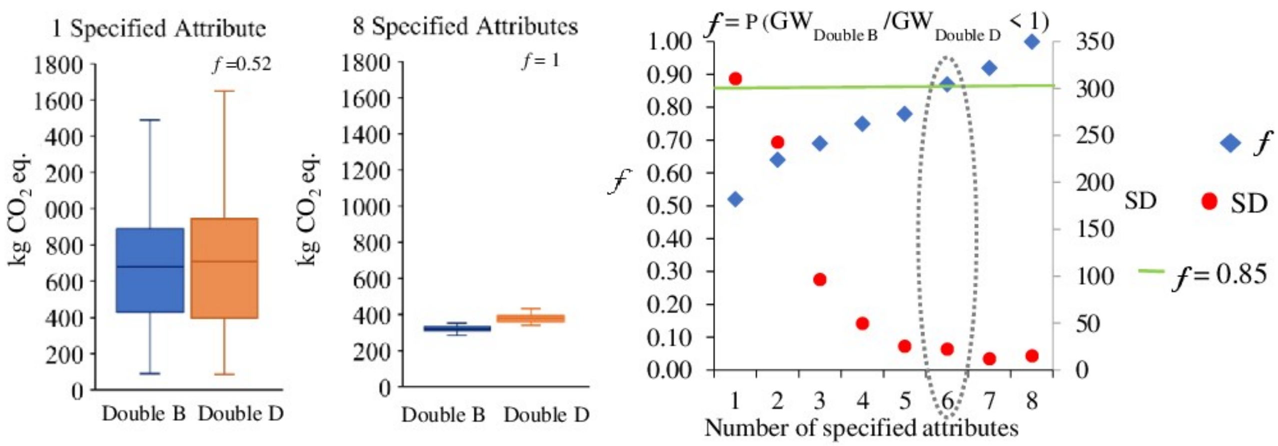


Figure 5.5 Global warming (GW) impacts for: two double-glazed solutions (Double B and Double D), using streamlined LCA model (the order of specified attributes: WWR, orientation, thermal transmittance value, solar factor, ventilation rate, number of occupants, and framing material)

For the life cycle cost assessment, the comparison indicator (CI) has been calculated as the ratio between the global costs (GC) of the two window solutions. The frequency of the results for the CI lower than 1, is demonstrated by f, as follows:

$$f = P\,(CI < 1) = P\,(GC_1/GC_2) < 1 \qquad (6)$$

Figure 5.6 shows the life cycle cost results for the two window solutions when only one attribute (i.e. glazing type: Double B vs. Double D) is specified and then when seven attributes are specified (WWR, orientation, framing material, thermal transmittance value, solar factor, ventilation rate, and number of occupants). In addition, Figure 5.6 shows the evolution of SD and f by increasing the number of specified attributes, indicating that the streamlined approach for the life cycle costs is effective when five attributes are specified.

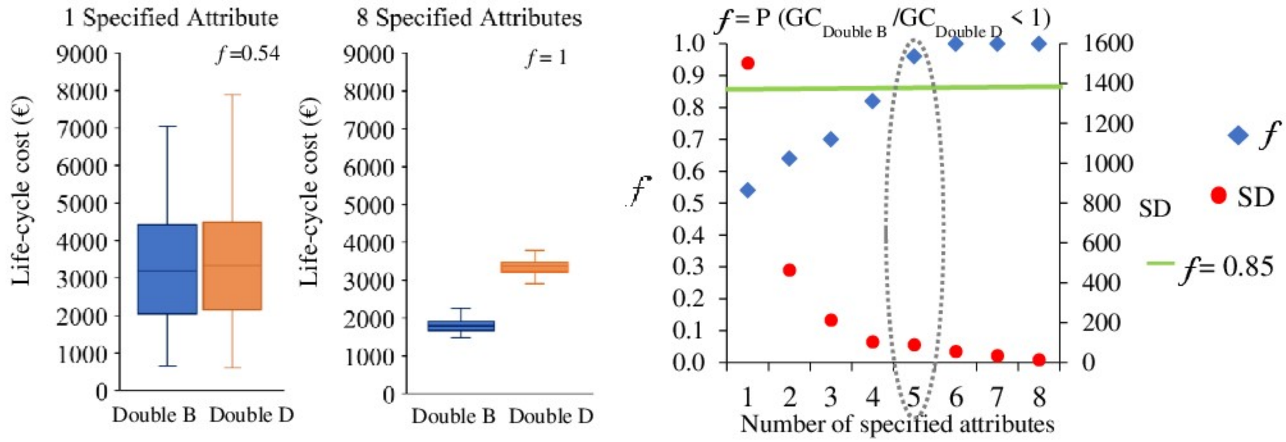


Figure 5.6 Life cycle cost (global cost GC) for: two double-glazed solutions (Double B and Double D), using streamlined LCA model (the order of specified attributes: WWR, orientation, framing material, thermal transmittance value, solar factor, ventilation rate, and number of occupants

5.3.3. Sequential specification of attributes analysis

This section primarily aims to present the attribute ranking using the standardized regression coefficient (SRC) for the consecutive set of sensitivity analyses. Then, the results of the streamlined environmental and cost LCA of a window are presented showing the sequential specification of attributes based on their ranking.

Figure 5.7 shows the standardized regression coefficient (SRC) results illustrating the relative contribution of each attribute to the global warming impacts and global costs of sequential sets of analyses. The first set of analysis includes 3456 scenarios combining all attributes listed in Table 5.1. In terms of both environmental and cost LCA of windows, the most influential attribute is WWR. Therefore, the next set of analysis consists of 1152 scenarios for three WWRs. The third most influential attribute in terms of both environmental and cost LCA of windows is the orientation to be assessed for the next set of analysis. Thus, the third set of analysis includes 288 scenarios for four orientations, where WWR was fixed at a standard size window area (WWR of 0.2) based on ISO 10077-1 (2017). Next, the results show the thermal transmittance value as the fourth influential attribute in terms of global warming impacts, while the framing type in terms of cost LCA to be assessed for the next set of analysis. Thus, the next set of analysis for the global warming impacts includes 144 scenarios for two U-values (Low-U: 0.96 W/(m^{2}K) and High-U: 2.56 W/(m^{2}K)), while for the life cycle cost, 72 scenarios were defined for four framing materials, with a WWR fixed at 0.2 and facing South. The next influential attribute in terms of global warming impacts is the solar factor, while in terms of life cycle cost is the thermal transmittance value to be assessed in the next set of analysis. Thus, the fifth set of analysis for global warming impacts includes 72 scenarios for two g-values (Low-g: 0.35, High-g: 0.78), where WWR was fixed at 0.2, facing

South with a U-value at 0.96 W/(m^2K) (low). In terms of life cycle cost, the fifth set of analysis includes 36 scenarios for two U-values (Low-U: 0.96 W/(m^2K) and High-U: 2.56 W/(m^2K)), where WWR was fixed at 0.2, facing South and PVC frame material. The next influential attribute in terms of global warming impacts is the ventilation rate, while in terms of life cycle cost solar factor to be assessed in the sixth set of analysis. Therefore, the sixth set of analysis for global warming impacts includes 36 scenarios for two ventilation rates (0.4 h^{-1}, 0.8 h^{-1}), where WWR was fixed at 0.2, facing South, a U-value at 0.96 W/(m^2K), and solar factor at 0.35 (low). In terms of life cycle cost, the sixth set of analysis includes 18 scenarios for two g-values (Low-g: 0.35, High-g: 0.78), where WWR was fixed at 0.2, facing South, with PVC frame and U-value at 0.96 W/(m^2K) (low). Subsequently, the next influential attributes in terms of global warming impacts are: number of occupants, framing type and then glazing type, while in terms of life cycle cost: ventilation rate, number of occupants and then glazing type, respectively.

Figure 5.7 Standardized regression coefficient (SRC) showing the relative contribution of each attribute to the global warming impacts and costs for alternative window orientations in Portugal, presented by sequential set of scenarios with refined attributes highlighted in each set of analysis. Each bar ranges from -1 to 1. Green bars represent positive correlation and red bars represent negative correlation

Figure 5.8 presents the streamlined environmental LCA of a window with sequential specification of the attributes. The attributes have been specified one by one based on the attribute ranking (Figure 5.7), until a reduced SD is obtained. The results show a reduction of SD up to 4 times by specifying just one attribute. Thus, the specification of fewer than 8 attributes can lead to robust results in the estimation of the windows global warming impacts.

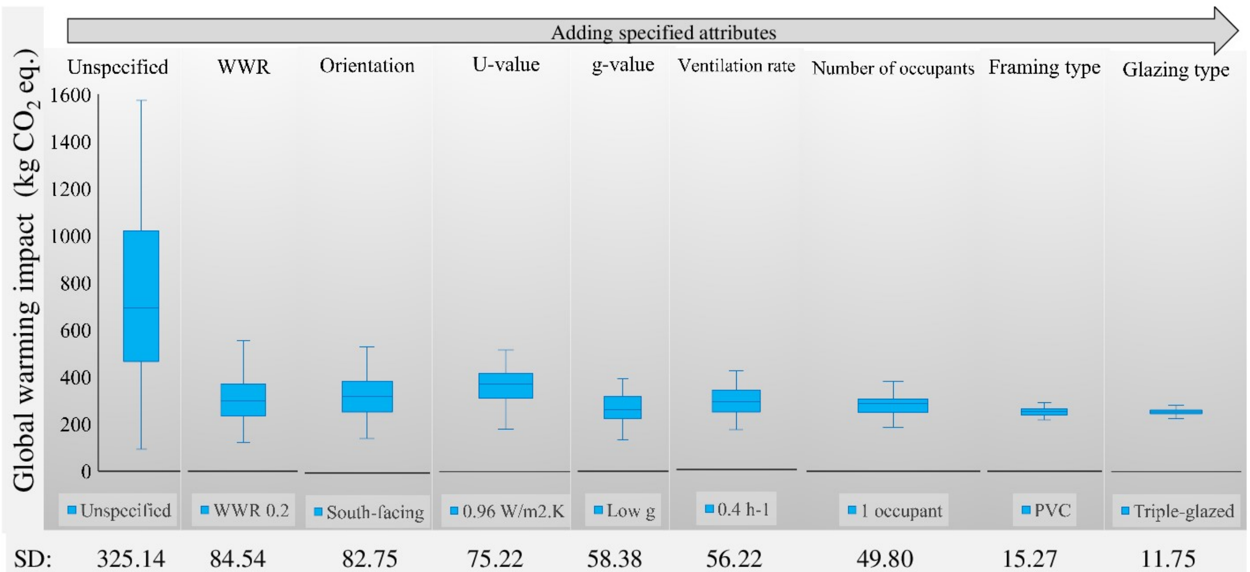


Figure 5.8 Global warming impact results and standard deviation (SD) for 8 levels of specified attributes, one to eight attributes are specified chronologically based on attribute ranking

Figure 5.9 presents the streamlined life cycle cost of a window with no specified attributes. Then, attributes have been specified one by one based on the attribute ranking (Figure 5.7), until a reduced SD is obtained. The life cycle cost results show the reduction of SD up to 11 times by specifying just one attribute. Therefore, the specification of fewer than 8 attributes can lead to robust results in the estimation of the windows life cycle costs.

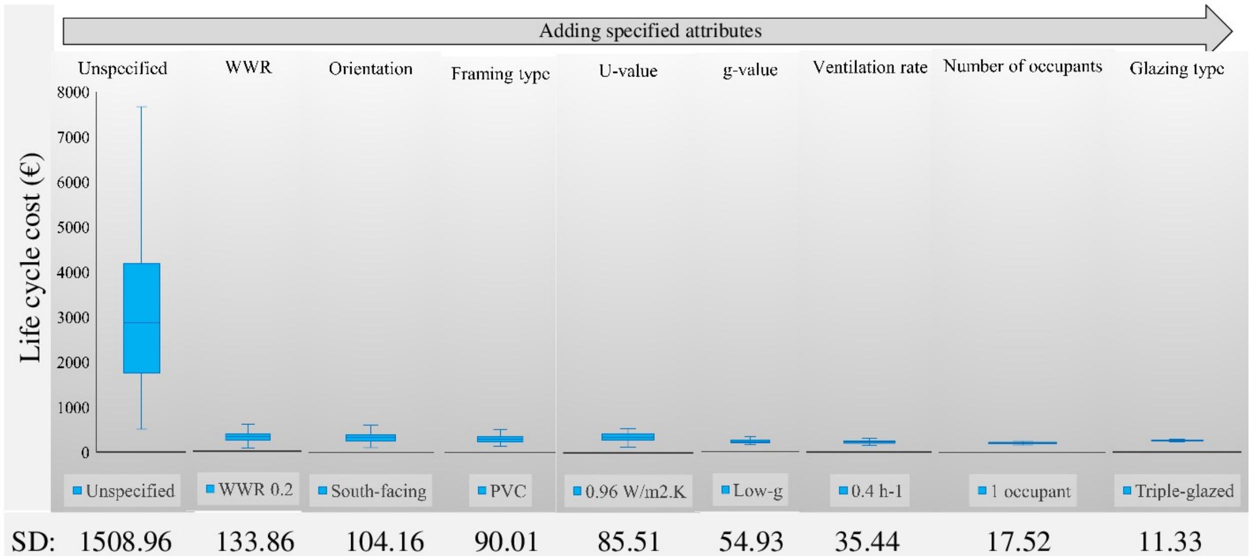


Figure 5.9 Total life cycle cost results and standard deviation (SD) for 8 levels of specified attributes, one to eight attributes are specified sequentially based on attribute rank*ing*

5.4. Concluding remarks

This chapter proposes a streamlined environmental and cost LCA approach to support early-stage decisions for the selection of windows. This approach assesses the cost and environmental performance of window solutions, with different levels of information specified, and reduces uncertainty in the results (by achieving low standard deviation) using attribute ranking by sequentially specifying attributes. Additionally, this chapter investigates the consistency of the results presented by this probabilistic approach compared to full LCA results (defined here as an LCA performed at late design stages of building design) using a reference office room located in Portugal. For demonstration purposes, a large range of windows was assessed, combining several glazing and frame alternatives, covering solutions with a large range of thermal transmittance and solar factor values.

The attribute ranking results shows that the most influential attributes in terms of global warming and global cost are window-to-wall ratio and orientation, respectively. Thermal transmittance value is identified as the thirdly most influential attribute in terms of global warming, while for global cost is the framing type. Next, solar factor is the most influential attribute for windows either with low or high U-values in terms of global warming, while U-value in terms of global cost for all types of frame materials. In case of low thermal transmittance solutions, ventilation rate shows a negative correlation with high solar factor windows in terms of both global warming and global cost. Glazing type is the lowest influential attribute in terms of both global warming and global cost.

The comparison of the results from the streamlined LCA model with a full LCA confirms that the results from the full LCA appear within the range of the results from the streamlined LCA model, in terms of global warming impacts and costs. In addition, the model acknowledged the similar preferred solutions as the full LCA by just specifying six attributes when comparing two window alternatives.

Following that, this chapter showed how a streamlined LCA can provide robust results to support the selection of appropriate window solutions, avoiding a time-consuming and resource-intensive full LCA. The approach developed can be further used to perform an environmental and cost LCA of future market window solutions with a wide range of values of thermal transmittance and solar factor. This model enables designers to select better window solutions to improve the cost and environmental performance of buildings.

6. Conclusions and recommendations

6.1. Key findings and contributions

This PhD thesis aims to implement an integrated cost and environmental LCA to support the selection of windows that minimize energy consumption, costs, and environmental impacts throughout the life cycle of windows. A streamlined environmental and cost LCA approach has been developed to support early-stage decisions for the selection of windows. A comprehensive cost and environmental LCA model combined with thermal dynamic simulation has been implemented for alternative window solutions, combining four framing materials (aluminum, PVC, fiberglass, and wood) and eight glazing alternatives (low versus high values for thermal transmittance and solar factors). Four cardinal directions and three distinct European climates (Coimbra, Berlin and Larnaca) have been assessed to explore how climate data and orientation influence the economic and environmental performance of the window solutions. Final energy (covering heating and cooling), environmental impacts and costs have been measured, and trade-offs identified using a bi-objective optimization (costs vs. environmental impacts).

A sensitivity analysis has been performed to identify the key drivers and rank the input parameters which contribute the most to variability of life cycle environmental impacts and costs of windows for different climates. 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 operation-related parameters (i.e. number of occupants and ventilation rate), have been investigated in three selected European locations (Coimbra, Berlin and Larnaca). The sensitivity analysis has been employed by calculating the standardized regression coefficient (SRC) method. The recognition of the key influential attributes can efficiently support the environmental and cost advice for the streamlined LCA.

The streamlined LCA approach aims to assess the cost and environmental performance of window solutions with different levels of information specified, as well as to reduce uncertainty in the estimated results by means of sequentially specifying attributes based on the attribute ranking. In addition, the consistency of the results presented by this approach has been compared to the full LCA results (defined here as an LCA performed at late-design stages of building design) using a reference office room located in Portugal. A large range of windows was assessed, combining several thermal transmittance values and solar factor for glazing and frame alternatives.

The responses and conclusions stemming from the research questions formulated in Chapter 1 (listed in Table 1.1) are presented below.

1. ***What is the contribution of individual components of the framing and glazing options to the total embodied impacts of a window solution?***

   The embodied impacts of window systems have been investigated by comparing alternative framing materials with other components (spacer, thermal break, weather stripping etc.), and glazing solutions with other components and attachments (coatings and gas-filled cavities), aiming to explore the contribution of each component to the overall embodied impacts of the window system. In addition, Pareto optimal frontiers have been calculated to identify the set of non-dominated window solutions in terms of thermal transmittance and embodied impacts.

   The embodied impacts calculated for the window systems show that for aluminum windows the contribution of the frame (>60% in all categories) is more significant than the glazing, while for wood-framed windows, the contribution of the framing is much less significant (<30% in all categories). For the PVC and fiberglass windows, the contribution of the framing varies depending on the glazing solution. Four window solutions appear on the Pareto frontier for all categories: a low-E coated triple-glazing (Triple A, non-tempered and laminated) with a wood or PVC frame and two single-glazed solutions with wood frame.

   The assessment of the glazing alternatives shows that the embodied impacts are highly influenced by the type of glass. Tempered glass leads to higher embodied impacts for the five categories due to the tempering process. For laminated glass, a polyynyl butyral (PVB) interlayer, 0.38 mm thick, accounts for about 20% of total global warming (GW) and non-renewable primary energy (NRPE) embodied impacts. It should also be noted that the glass coating is one of the components with highest eutrophication (EU) impact due to the electricity consumed in the production process. A low-E film (copper oxide) contributes to approximately 35% of the total embodied eutrophication of the glazing system.

   Regarding the framing materials, wood has the lowest embodied impacts, while aluminum frame has the highest. In the aluminum frame, the thermal break is responsible for up to 23% of the embodied impacts. Results for PVC frames show that the stainless steel used to ensure good mechanical resistance reaches a share of up to 29% of the embodied impacts.

2. ***What are the trade-offs between embodied and operational environmental impacts of window solutions?***

   An environmental life cycle assessment of alternative window solutions for a reference office room has been performed, involving embodied and operational (heating and cooling) environmental impacts. Thermal dynamic simulation has been implemented to assess the operational performance of 32 alternative window solutions in office use.

   Life cycle impact results show that glazing is the component with the greatest influence on the total environmental impacts (mainly operational because of heating and cooling energy needs). The impacts are highly dependent on the thermal transmittance values and solar factors; glazing solutions with the lowest solar factor showed lower operational (cooling) impacts in warm climates, and those with the lowest thermal transmittance values had lower operational (heating) impacts in cold climates. Framing options lead to slight differences in the overall impacts, mainly associated with the embodied impacts.

3. ***How to select optimal windows that minimize energy consumption, costs, and environmental impacts throughout the life cycle of windows?***

   The optimal window solutions that maximize life cycle benefits depend on the climate data and the orientation of the building. Low-solar factor solution is more beneficial in warm climate zones, and low thermal transmittance windows are better in cold climate zones. Even though the frame option does not offer significant operational savings, it can lead to lower embodied impacts. The results of this work have shown that the Pareto optimal window solutions in terms of economic criteria are the PVC-framed windows because of the low initial investment in the PVC frame. The Pareto optimal window solutions for all environmental impact categories in warm climates lead to the low solar factor windows with a PVC or wood frame. For cold climates, the Pareto optimal window solutions are associated with the window solutions with a low thermal transmittance value and with a PVC or wood frame.

4. ***What are the key drivers and ranking the parameters that contribute the most to the variability in cost and environmental performance of windows, considering various European climates?***

   A sensitivity analysis has been performed to identify the key drivers and rank the input parameters which contribute the most to variability of environmental life cycle impacts (global warming) and costs of windows for three European climates. 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 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 has been 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 has been 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 Coimbra and Larnaca, number of occupants presents a negative correlation in windows with a low solar factor and facing North. Ventilation rate presents a positive correlation in all scenarios, except with in windows with high solar factor and facing South. In Berlin, solar factor and number of occupants have negative correlation in smaller windows, meaning that an increase of these parameters leads to lower environmental impacts.

Thermal transmittance value has been identified as the third most influential parameter in warmer locations. In Coimbra and Larnaca, number of occupants presents a high positive correlation in windows with low solar factor and low thermal transmittance, except in the North orientation. In Larnaca, number of occupants presents a high positive correlation in windows with a low solar factor. Instead, ventilation rate has been identified as the third most influential parameter in Berlin. It was shown that a high solar factor combined with a high ventilation rate ($0.8\ h^{-1}$) lead to lower environmental impacts.

5. ***Can a streamlined environmental and cost LCA approach support the selection of windows in early-design stages of office buildings?***

A streamlined environmental and cost LCA approach has been developed to support early-stage decisions for the selection of windows. This approach assesses the cost and environmental performance of window solutions with different levels of information specified, as well as to reduce uncertainty in the estimated results by means of sequentially specifying attributes based on the attribute ranking. Additionally, the consistency of the results presented by the streamlined approach has been compared to the full LCA results (defined here as an LCA performed at late design stages of building design) using a reference office room located in Portugal. A large range of windows was assessed, combining several thermal transmittance values and solar factor for glazing and frame alternatives, different window orientation and dimensions, as well as varying operation-related parameters (i.e. number of occupants and ventilation rate). The comparison of the results from the streamlined LCA model with the full LCA shows that the results from the full LCA appear within the range of the results from the streamlined LCA model, in terms of life cycle global warming impacts and costs. In addition, the streamlined model the similar preferred solutions as the full LCA by just specifying six attributes when comparing two window alternatives.

6.2. Potential impacts and recommendations

This PhD thesis has a potential impact to support the accuracy and robustness of information provided in the early-stage design of the buildings in terms of cost and environmental performance of windows. Moreover, the thesis may promote improved environmental actions among window manufacturers and suppliers, window buyers, and designers, particularly in the European market. This PhD research covers a large range of windows in the market in terms of thermal transmittance and solar factor for the glazing and frame solutions. Hence, the developed approach can contribute to the estimation of an environmental and cost LCA of future market window solutions with values of thermal transmittance and solar factor differing from those presented in this study. The streamlined model developed in this thesis can contribute to support the accurate and robust information for the environmental and cost performance of windows with limited inventory data about most design attributes. This model enables designers to select better window solutions to improve the cost and environmental performance of buildings. Last but not least, this research PhD shows that it is not essential to perform a time-consuming and resource-intensive full LCA to select most appropriate window solutions in terms of environmental and cost performances. In summary, this PhD research can have impact in:

- Helping the building and window designers through providing insights on the key drivers that affect the environmental and cost LCA of windows,

- Supporting the accuracy and robustness of information provided in the early-stage design of the buildings in terms of cost and environmental performance of windows,
- Promoting improved environmental actions among window manufacturers and suppliers, window buyers, and designers, particularly in the European market,
- Contributing to the estimation of an environmental and cost LCA of future market window solutions with a wide range of values of thermal transmittance and solar factor,
- Supporting the accurate and robust information for the environmental and cost performance of windows with limited inventory data about most design attributes,
- Motivating the integration of economic and environmental LCA approaches in window design practices,
- Confirming the difficulty of performing a full LCA to select the most appropriate window solution in terms of environmental and cost performances, as a time-consuming and resource-intensive tool,
- Streamlining LCA and LCC of windows to become more user-friendly in order to support the selection of windows.

6.3. Limitations and further research

The results of this research are valid for European climates, since the reference building, construction and window characteristics, range of window- and operation-related parameters, as well as other assumptions implemented for the model are chiefly based on European office buildings. Future work of full and streamlined environmental and cost LCA of windows can assess other building types (e.g., residential or commercial), or building from different periods, as well as additional climate regions (non-European).

Moreover, this study estimated operational energy needs covering heating and cooling, overlooking the lighting energy needs. As window solutions might have an important contribution to the lighting energy needs, a comparative assessment of the operational lighting impacts for different window solutions could also be the subject to further research.

Windows may influence indoor air quality (living conditions); however, air quality parameters have not been considered in this thesis, but may be considered in further research, as well as using adaptive thermal comfort methods to define occupancy and thermal comfort scenarios. Indoor air quality attributes, as well as lighting energy attributes could be combined for the energy model developed by the streamlined LCA approach.

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Appendix I Thesis main publications

Most of this PhD thesis is based on the following key articles that are published or submitted to Web of Science journals. Afterwards, abstracts and keywords for the articles are presented.

Chapter 2:

- **Saadatian, S.**, Freire, F., Simões, N. (2021). "Embodied impacts of window systems: a comparative assessment of framing and glazing alternatives", Journal of Building Engineering, vol. 35, Article 102042. https://doi.org/10.1016/j.jobe.2020.102042.

JCR® impact factor (2021): 5.318

Chapter 3:

- **Saadatian, S.**, Simões, N., Freire, F. (2021). "Integrated environmental, energy and cost life-cycle analysis of windows: Optimal selection of components", Building and Environment, vol. 188, Article 107516. https://doi.org/10.1016/j.buildenv.2020.107516.

JCR® impact factor (2021): 6.456

Chapter 4:

- **Saadatian, S.**, Rodrigues, C., Freire, F., & Simões, N. (2022). "Key drivers of life-cycle environmental and cost assessment of windows for different European climate zones", Journal of Building Engineering, vol. 50, 104206. https://doi.org/10.1016/j.jobe.2022.104206.

JCR® impact factor (2021): 5.318

Chapter 5:

- **Saadatian, S.**, Rodrigues, C., Freire, F., Simões, N. (2021). "Environmental and cost life-cycle approach to support selection of windows in early stages of building design", submitted to Journal of Cleaner Production (Under Review)

JCR® impact factor (2021): 9.297

Embodied impacts of window systems: a comparative assessment of framing and glazing alternatives[5]

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Abstract

The embodied impacts of window materials can be considered as hidden impacts. However, as buildings have become more energy efficient, the impacts of the windows are recognized as being increasingly significant and have not been thoroughly analyzed. Thus, comprehensive analysis should be performed to inform the wise selection of energy-efficient windows with lower embodied impacts. This article proposes an approach based on embodied impact assessment and Pareto optimal frontier to support environmentally friendly design of windows. A comprehensive assessment of the embodied environmental impacts of a standard size window was implemented for 32 alternative systems, considering four framing materials (aluminum, fiberglass, polyvinyl chloride, wood) and eight glazing solutions (for single-, double, tripled-glazed). Environmental impacts were calculated for non-renewable primary energy, global warming, acidification, eutrophication, and ozone layer depletion. Pareto optimal frontiers were identified, showing the trade-offs between environmental impacts and thermal transmittance (U-value). The components of the two main parts of a window (frame and glass) have been characterized to identify those that contribute most to the total embodied impacts. The results show that tempered or laminated glass and the glass coating (low-E film) increase the embodied impacts of glazing solutions. Of the framing materials, wood has the lowest embodied impacts in all categories, while aluminum has the highest impacts for the double and triple-glazed solutions. The breakdown of the embodied impacts of aluminum-framed window systems shows that the frame has higher impacts than the glazing, as it accounts for 60-80% of total embodied impacts. In the windows with polyvinyl chloride (PVC) and fiberglass frames, the frame is responsible for most of the embodied impacts for single-glazed windows (58-86%) and almost the same proportion for double-glazed windows (46-54%), but lower for triple-glazed (22-40%). The contribution of a wood frame (<30%) is much less significant. Pareto optimal frontiers are identified for the window systems and the non-dominated solutions are discussed for the various environmental impact categories.

Keywords Embodied impact; cradle-to-site; window system; glazing; framing; Pareto frontier

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[5] Saadatian, S., Freire, F., Simões, N. (2021). "Embodied impacts of window systems: a comparative assessment of framing and glazing alternatives", Journal of Building Engineering, vol. 35, Article 102042. https://doi.org/10.1016/j.jobe.2020.102042.

Integrated environmental, energy and cost life-cycle analysis of windows: optimal selection of components[6]

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Abstract

There is an increasing need for energy-efficient windows; however, these windows can have high embodied impacts and can be costly. This has not been thoroughly analyzed and the literature has mainly focused on the operational performance of windows. It is important to wisely select optimal windows that minimize energy consumption, costs, and environmental impacts throughout their lifecycle, considering the influence of window orientation and climate data. This article presents an integrated cost and environmental life-cycle assessment (LCA) of window solutions, combining alternative glazing and framing options. Optimal window solutions were selected using a Pareto bi-objective optimization (costs vs. environmental impacts) for three different European climate regions, considering various window orientations. The influence of each window component (glazing and framing), as well as window properties (thermal transmittance and solar factor) on the overall environmental and cost life-cycle impacts was studied. Pareto optimal window solutions for warm climates highlight low solar factor windows, while for cold climates they highlight low thermal transmittance value. The glazing is the component with the greatest influence on the total environmental impacts (mainly operational). The impacts depend to a very great extent on the thermal transmittance values and solar factors. The life-cycle cost analysis shows that the initial investment in the windows has a high impact on the overall cost, even when a lifespan of 30 years is considered. This article provides insights into and recommendations for the design of windows by addressing different climatic conditions and window orientations.

Keywords Environmental impacts; Life-cycle costing; Windows; Pareto solutions; Building energy consumption

[6] Saadatian, S., Simões, N., Freire, F. (2021). "Integrated environmental, energy and cost life-cycle analysis of windows: Optimal selection of components", Building and Environment, vol. 188, Article 107516. https://doi.org/10.1016/j.buildenv.2020.107516.

Key drivers of life-cycle environmental and cost assessment of windows for different European climate zones[7]

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Abstract

Windows are challenging building components regarding their life-cycle environmental and economic performances, which are influenced by parameters that often present trade-offs between environmental impacts and costs. It is essential to identify the key drivers of environmental impacts and cost of windows to reduce the time and effort needed to perform a life-cycle assessment (LCA) and support the selection of windows with the best combined environmental and cost performance in an early-design stage of buildings. 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. In addition, 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, while in colder climates on bigger windows. 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.

Keywords: window-related parameters, operation-related parameters, life-cycle assessment, Life-cycle cost, sensitivity analysis, climate regions

[7] Saadatian, S., Rodrigues, C., Freire, F., & Simões, N. (2022). "Key drivers of life-cycle environmental and cost assessment of windows for different European climate zones", Journal of Building Engineering, vol. 50, 104206. https://doi.org/10.1016/j.jobe.2022.104206

Environmental and cost life-cycle approach to support selection of windows in early stages of building design[8]

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Abstract

The selection of windows with the lowest life-cycle environmental impacts in an early-design stage is important to minimize impacts of buildings. Hence, an environmental and cost streamlined life-cycle assessment (LCA) approach, incorporating probabilistic triage, has been developed to support early-decision making for selection of window materials and components. This approach permits also to reduce the uncertainty in the estimated results by means of sequentially specifying attributes based on the attribute ranking. For demonstration purposes, a large number of window alternatives has been assessed for a reference office room. This approach proved to be effective in providing robust results to support the selection of windows by specifying very few window-related attributes (less than 8). The attribute ranking results show that the most influential attributes in terms of cost and environmental LCA are window-to-wall ratio and orientation, respectively. Future market window solutions with a wide range of alternative materials and components, impacting thermal transmittance and solar factor values, can be assessed using this approach to find optimal cost and environmental performance of buildings.

Keywords: windows, early-stage decisions, life-cycle assessment, life-cycle cost, probabilistic triage

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[8] Saadatian, S., Rodrigues, C., Freire, F., Simões, N. (2021). "Environmental and cost life-cycle approach to support selection of windows in early stages of building design", submitted to Journal of Cleaner Production (Under Review)

Appendix II Integrated environmental, energy and cost life cycle analysis of windows

This section firstly presents the reference office building scheme and the constructions characteristics introduced by Corgnati et al. (2013) by Figure A. 1 and Table A. 1, respectively. This building has been considered as the second case study in order to assess the behavior of the window solutions within a different building (See Section 3.2.1.2.2). In addition, the additional detailed information for Figure 3.1 with the full results is documented in Table A. 2.

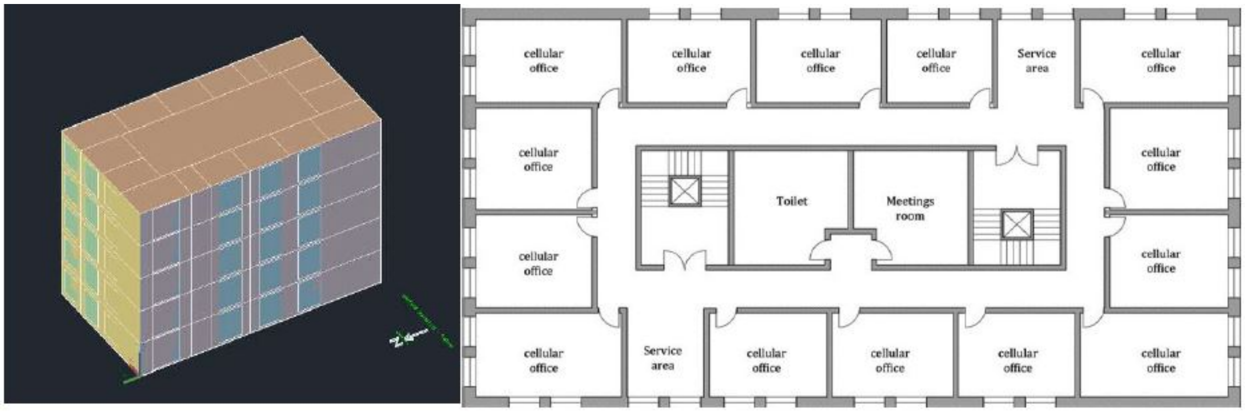

Figure A. 1 The reference office building scheme introduced by Corgnati et al. (2013)

Table A. 1 The constructions characteristics of the reference office building introduced by Corgnati et al. (2013)

Number of floors	Building total height (m)	Wall area (m^2)	Window area (m^2)	Gross roof area (m^2)	Gross total area (m^2)	Gross area of typical floor (m^2)	Volume (m^3)
5	14.5	1296	588	450	2400	540	34800

Table A. 2 Life cycle environmental impacts of 30-year use of the office room in Coimbra, comparing different window solutions facing in four directions

Non-renewable primary energy [MJ]

Framing solution	Glazing solution	Opaque envelope	Framing	Glazing	Heating (South)	Cooling (South)	Heating (North)	Cooling (North)	Heating (West)	Cooling (West)	Heating (East)	Cooling (East)
No window		1666.2	0.0	0.0	9026.2	344.9	11363.4	90.9	10350.9	356.9	10335.5	339.8
No frame	SA	1365.3	0.0	265.8	1839.6	31363.3	13360.8	6589.4	7996.6	28619.4	8339.8	23878.1
	SB	1365.3	0.0	568.0	9705.7	6040.3	19114.5	892.3	14951.5	7092.2	15131.7	5130.8
	DA	1365.3	0.0	862.6	2356.1	7773.5	9206.3	1750.3	6347.5	9506.6	6462.5	7533.2
	DB	1365.3	0.0	740.1	171.6	24506.2	6320.0	6371.5	3565.8	24332.9	3739.2	20557.7
	DC	1365.3	0.0	1396.3	2362.9	8315.7	9475.8	1870.4	6524.2	10072.9	6649.5	8003.4
	DD	1365.3	0.0	1001.0	398.1	31680.8	8195.6	7507.5	4612.6	29118.8	4835.7	24665.8
	TA	1365.3	0.0	1146.9	66.9	24200.7	5278.4	6586.0	2891.5	24159.6	3045.9	20489.0
	TB	1365.3	0.0	1542.4	248.8	18867.4	6405.8	5177.2	3787.2	20420.4	3950.2	17108.5
Aluminum	SA	1365.3	706.7	221.8	2024.9	31505.8	13906.5	6374.9	8348.3	28374.1	8646.9	23854.1
	SB	1365.3	741.7	477.9	10260.0	6067.8	19890.2	876.9	15632.8	6956.7	15773.5	5075.9
	DA	1365.3	2192.4	601.9	3143.7	7214.1	10345.8	1455.2	7346.2	8852.8	7480.0	6920.6
	DB	1365.3	2192.4	540.9	312.3	22994.4	7178.0	5853.3	4149.3	23255.2	4331.2	19552.1
	DC	1365.3	2192.4	937.8	3287.9	6532.8	10555.1	1403.7	7550.4	8734.4	7710.0	6735.3
	DD	1365.3	2182.4	688.9	381.0	31852.4	8109.8	7560.7	4552.5	29235.5	4773.9	24775.6
	TA	1365.3	1979.6	895.9	166.5	22498.5	6119.3	6007.7	3490.3	22960.1	3656.8	19363.3
	TB	1365.3	2009.6	1138.8	410.1	17820.7	7114.5	4779.1	4293.4	19625.9	4459.9	16338.0
PVC	SA	1365.3	1379.7	213.2	1204.6	35263.8	11708.3	7411.4	6769.6	30896.6	7011.6	26277.1
	SB	1365.3	1372.7	460.1	8238.5	6486.5	17577.0	935.2	13486.0	7649.9	13631.9	5637.1
	DA	1365.3	1045.9	586.6	2639.2	7529.8	9616.5	1635.3	6730.2	9247.5	6853.7	7286.1
	DB	1365.3	1046.9	523.7	217.9	23939.9	6616.9	6179.3	3776.9	23931.3	3953.7	20185.3
	DC	1365.3	1045.9	919.3	2531.1	8156.1	9731.4	1793.2	6737.0	9899.6	6869.1	7843.8
	DD	1365.3	1043.9	671.5	278.0	32966.1	7571.0	7905.6	4175.0	29995.7	4391.2	25491.2
	TA	1365.3	1216.2	870.1	125.3	23071.6	5820.7	6205.1	3277.6	23368.5	3440.6	19744.3
	TB	1365.3	1199.7	1080.5	327.8	18294.3	6783.3	4959.2	4056.6	19988.0	4221.4	16688.1
Fiberglass	SA	1365.3	550.6	220.4	1288.7	32995.2	11795.8	7289.6	6925.8	30095.2	7270.7	25074.2
	SB	1365.3	547.6	474.9	8485.6	6131.3	17667.9	926.6	13635.3	7457.7	13836.1	5388.2
	DA	1365.3	626.1	630.0	2805.7	7449.2	9894.5	1570.1	6956.7	9130.8	7078.5	7181.5
	DB	1365.3	627.3	538.0	257.4	23521.2	6845.1	6035.2	3938.2	23632.8	4118.4	19905.6
	DC	1365.3	626.1	1024.0	2723.3	7991.4	10000.8	1717.7	6973.8	9722.9	7111.1	7672.2
	DD	1365.3	786.9	662.6	248.8	33338.4	7408.0	8018.9	4054.9	30246.2	4235.1	25726.3
	TA	1365.3	759.9	891.6	135.6	22937.8	5889.3	6158.7	3327.3	23272.4	3490.3	19655.1

	TB	1365.3	772.9	1093.1	338.1	18223.9	6831.4	4933.5	4089.2	19934.8	4255.7	16636.6
Wood	SA	1365.3	146.5	196.6	1043.3	33789.8	10965.2	7708.3	6359.5	30882.9	6716.4	25681.7
	SB	1365.3	146.1	425.6	7649.9	6387.0	16708.7	1000.4	12746.4	7907.3	12964.4	5733.2
	DA	1365.3	144.5	568.7	2850.3	7330.8	9892.7	1565.0	6973.8	9053.6	7107.7	7088.8
	DB	1365.3	144.6	490.3	248.8	23603.6	6798.8	6064.3	3905.6	23691.1	4084.1	19960.5
	DC	1365.3	144.5	918.1	2689.0	8020.6	9951.1	1731.4	6930.9	9753.7	7066.5	7703.1
	DD	1365.3	144.3	654.8	312.3	32556.0	7764.9	7778.6	4310.6	29717.7	4530.2	25230.3
	TA	1365.3	142.2	820.1	166.5	22498.5	6119.3	6007.7	3490.3	22960.1	3656.8	19363.3
	TB	1365.3	143.5	1064.1	405.0	17853.3	7090.5	4791.1	4276.3	19651.6	4442.7	16362.1

Global warming [kg CO_2 eq.]

Framing solution	Glazing solution	Opaque envelope	Framing	Glazing	Heating (South)	Cooling (South)	Heating (North)	Cooling (North)	Heating (West)	Cooling (West)	Heating (East)	Cooling (East)
No window		92.22	0.00	0.00	719.57	27.50	905.89	7.25	825.18	28.45	823.95	27.09
No frame	SA	75.57	0.00	21.66	146.65	2500.29	1065.12	525.31	637.49	2281.55	664.85	1903.57
	SB	75.57	0.00	45.51	773.74	481.54	1523.82	71.14	1191.94	565.39	1206.30	409.03
	DA	75.57	0.00	70.34	187.83	619.70	733.93	139.54	506.02	757.87	515.19	600.55
	DB	75.57	0.00	59.45	13.68	1953.64	503.83	507.94	284.27	1939.82	298.09	1638.86
	DC	75.57	0.00	113.92	188.37	662.93	755.41	149.11	520.11	803.02	530.10	638.04
	DD	75.57	0.00	78.56	31.74	2525.60	653.36	598.50	367.72	2321.36	385.50	1966.36
	TA	75.57	0.00	93.02	5.34	1929.29	420.80	525.04	230.51	1926.01	242.82	1633.39
	TB	75.57	0.00	119.08	19.84	1504.12	510.67	412.73	301.92	1627.92	314.91	1363.90
Aluminum	SA	75.57	63.90	18.08	161.42	2511.65	1108.63	508.21	665.53	2261.99	689.34	1901.66
	SB	75.57	67.10	38.35	817.93	483.72	1585.65	69.90	1246.25	554.59	1257.47	404.65
	DA	75.57	173.55	48.56	250.62	575.11	824.77	116.01	585.64	705.75	596.31	551.71
	DB	75.57	173.55	44.30	24.90	1833.12	572.23	466.62	330.78	1853.91	345.28	1558.70
	DC	75.57	173.55	75.44	262.11	520.80	841.46	111.90	601.92	696.31	614.64	536.94
	DD	75.57	172.55	52.87	30.37	2539.28	646.52	602.74	362.93	2330.66	380.58	1975.12
	TA	75.57	160.77	73.29	13.27	1793.58	487.83	478.94	278.25	1830.38	291.52	1543.65
	TB	75.57	163.77	88.26	32.70	1420.67	567.17	380.99	342.27	1564.58	355.54	1302.47
PVC	SA	75.57	69.52	17.38	96.03	2811.24	933.39	590.84	539.68	2463.08	558.96	2094.82
	SB	75.57	69.22	36.92	656.78	517.10	1401.24	74.56	1075.11	609.85	1086.74	449.39
	DA	75.57	51.19	47.32	210.40	600.28	766.63	130.37	536.53	737.22	546.38	580.85
	DB	75.57	51.29	42.90	17.37	1908.50	527.50	492.62	301.10	1907.81	315.19	1609.18
	DC	75.57	51.19	73.95	201.78	650.21	775.79	142.96	537.08	789.20	547.61	625.31
	DD	75.57	51.19	51.51	22.16	2628.06	603.56	630.24	332.83	2391.26	350.07	2032.16
	TA	75.57	61.84	71.19	9.99	1839.28	464.03	494.67	261.29	1862.94	274.28	1574.02
	TB	75.57	57.72	83.93	26.13	1458.42	540.77	395.35	323.40	1593.45	336.53	1330.38

Fiberglass	SA	75.57	33.87	17.96	102.74	2630.39	940.36	581.13	552.12	2399.20	579.62	1998.92
	SB	75.57	33.67	38.11	676.48	488.79	1408.49	73.87	1087.01	594.53	1103.02	429.55
	DA	75.57	32.97	50.84	223.67	593.85	788.79	125.17	554.59	727.91	564.30	572.51
	DB	75.57	32.97	44.07	20.52	1875.12	545.70	481.13	313.96	1884.01	328.32	1586.88
	DC	75.57	32.97	82.41	217.10	637.08	797.27	136.94	555.96	775.11	566.90	611.63
	DD	75.57	47.94	50.92	19.84	2657.75	590.57	639.27	323.26	2411.24	337.62	2050.91
	TA	75.57	46.04	72.94	10.81	1828.61	469.50	490.98	265.26	1855.28	278.25	1566.91
	TB	75.57	46.94	84.98	26.95	1452.82	544.60	393.30	325.99	1589.21	339.26	1326.28
Wood	SA	75.57	6.69	16.02	83.17	2693.73	874.15	614.51	506.98	2461.99	535.44	2047.35
	SB	75.57	6.66	34.13	609.85	509.17	1332.02	79.75	1016.15	630.37	1033.52	457.05
	DA	75.57	6.54	45.88	227.22	584.41	788.65	124.76	555.96	721.76	566.63	565.12
	DB	75.57	6.55	40.18	19.84	1881.68	542.00	483.45	311.36	1888.66	325.58	1591.26
	DC	75.57	6.54	73.87	214.37	639.40	793.30	138.03	552.54	777.57	563.34	614.10
	DD	75.57	6.53	50.15	24.90	2595.37	619.02	620.11	343.64	2369.10	361.15	2011.37
	TA	75.57	6.37	67.10	13.27	1793.58	487.83	478.94	278.25	1830.38	291.52	1543.65
	TB	75.57	6.47	82.42	32.28	1423.27	565.26	381.95	340.91	1566.63	354.18	1304.39

Acidification [kg SO2 eq.]

Framing solution	Glazing solution	Opaque envelope	Framing	Glazing	Heating (South)	Cooling (South)	Heating (North)	Cooling (North)	Heating (West)	Cooling (West)	Heating (East)	Cooling (East)
No window		0.564	0.000	0.000	1.925	0.074	2.424	0.019	2.208	0.076	2.204	0.072
No frame	SA	0.462	0.000	0.109	0.392	6.689	2.850	1.405	1.706	6.104	1.779	5.093
	SB	0.462	0.000	0.231	2.070	1.288	4.077	0.190	3.189	1.513	3.227	1.094
	DA	0.462	0.000	0.329	0.503	1.658	1.964	0.373	1.354	2.028	1.378	1.607
	DB	0.462	0.000	0.271	0.037	5.227	1.348	1.359	0.761	5.190	0.798	4.385
	DC	0.462	0.000	0.482	0.504	1.774	2.021	0.399	1.392	2.148	1.418	1.707
	DD	0.462	0.000	0.334	0.085	6.757	1.748	1.601	0.984	6.211	1.031	5.261
	TA	0.462	0.000	0.459	0.014	5.162	1.126	1.405	0.617	5.153	0.650	4.370
	TB	0.462	0.000	0.505	0.053	4.024	1.366	1.104	0.808	4.355	0.843	3.649
Aluminum	SA	0.462	0.299	0.091	0.432	6.720	2.966	1.360	1.781	6.052	1.844	5.088
	SB	0.462	0.314	0.194	2.188	1.294	4.242	0.187	3.334	1.484	3.364	1.083
	DA	0.462	0.763	0.244	0.671	1.539	2.207	0.310	1.567	1.888	1.595	1.476
	DB	0.462	0.764	0.235	0.067	4.904	1.531	1.248	0.885	4.960	0.924	4.170
	DC	0.462	0.763	0.337	0.701	1.393	2.251	0.299	1.610	1.863	1.644	1.437
	DD	0.462	0.762	0.241	0.081	6.794	1.730	1.613	0.971	6.236	1.018	5.284
	TA	0.462	0.734	0.386	0.036	4.799	1.305	1.281	0.744	4.897	0.780	4.130
	TB	0.462	0.746	0.422	0.087	3.801	1.517	1.019	0.916	4.186	0.951	3.485
PVC	SA	0.462	0.223	0.087	0.257	7.521	2.497	1.581	1.444	6.590	1.495	5.605

	SB	0.462	0.222	0.187	1.757	1.383	3.749	0.199	2.876	1.632	2.908	1.202
	DA	0.462	0.166	0.238	0.563	1.606	2.051	0.349	1.435	1.972	1.462	1.554
	DB	0.462	0.166	0.228	0.046	5.106	1.411	1.318	0.806	5.104	0.843	4.305
	DC	0.462	0.166	0.330	0.540	1.740	2.076	0.382	1.437	2.111	1.465	1.673
	DD	0.462	0.166	0.235	0.059	7.031	1.615	1.686	0.890	6.398	0.937	5.437
	TA	0.462	0.202	0.697	0.027	4.921	1.241	1.323	0.699	4.984	0.734	4.211
	TB	0.462	0.187	0.404	0.070	3.902	1.447	1.058	0.865	4.263	0.900	3.559
Fiberglass	SA	0.462	0.191	0.090	0.275	7.037	2.516	1.555	1.477	6.419	1.551	5.348
	SB	0.462	0.190	0.193	1.810	1.308	3.768	0.198	2.908	1.591	2.951	1.149
	DA	0.462	0.185	0.255	0.598	1.589	2.110	0.335	1.484	1.947	1.510	1.532
	DB	0.462	0.186	0.234	0.055	5.017	1.460	1.287	0.840	5.041	0.878	4.246
	DC	0.462	0.185	0.368	0.581	1.704	2.133	0.366	1.487	2.074	1.517	1.636
	DD	0.462	0.270	0.233	0.053	7.111	1.580	1.710	0.865	6.451	0.903	5.487
	TA	0.462	0.259	0.384	0.029	4.892	1.256	1.314	0.710	4.964	0.744	4.192
	TB	0.462	0.264	0.409	0.072	3.887	1.457	1.052	0.872	4.252	0.908	3.548
Wood	SA	0.462	0.034	0.080	0.223	7.207	2.339	1.644	1.356	6.587	1.433	5.478
	SB	0.462	0.034	0.173	1.632	1.362	3.564	0.213	2.719	1.687	2.765	1.223
	DA	0.462	0.033	0.230	0.608	1.564	2.110	0.334	1.487	1.931	1.516	1.512
	DB	0.462	0.033	0.215	0.053	5.034	1.450	1.293	0.833	5.053	0.871	4.257
	DC	0.462	0.033	0.330	0.574	1.711	2.122	0.369	1.478	2.080	1.507	1.643
	DD	0.462	0.033	0.228	0.067	6.944	1.656	1.659	0.919	6.338	0.966	5.381
	TA	0.462	0.032	0.355	0.036	4.799	1.305	1.281	0.744	4.897	0.780	4.130
	TB	0.462	0.033	0.395	0.086	3.808	1.512	1.022	0.912	4.191	0.948	3.490

Eutrophication [kg (PO4)3 eq.]

Framing solution	Glazing solution	Opaque envelope	Framing	Glazing	Heating (South)	Cooling (South)	Heating (North)	Cooling (North)	Heating (West)	Cooling (West)	Heating (East)	Cooling (East)
No window		0.112	0.000	0.000	1.357	0.052	1.708	0.014	1.556	0.054	1.554	0.051
No frame	SA	0.092	0.000	0.033	0.277	4.715	2.009	0.991	1.202	4.303	1.254	3.590
	SB	0.092	0.000	0.067	1.459	0.908	2.874	0.134	2.248	1.066	2.275	0.771
	DA	0.092	0.000	0.121	0.354	1.169	1.384	0.263	0.954	1.429	0.972	1.133
	DB	0.092	0.000	0.098	0.026	3.684	0.950	0.958	0.536	3.658	0.562	3.091
	DC	0.092	0.000	0.178	0.355	1.250	1.425	0.281	0.981	1.514	1.000	1.203
	DD	0.092	0.000	0.124	0.060	4.763	1.232	1.129	0.694	4.378	0.727	3.708
	TA	0.092	0.000	0.175	0.010	3.639	0.794	0.990	0.435	3.632	0.458	3.081
	TB	0.092	0.000	0.176	0.037	2.837	0.963	0.778	0.569	3.070	0.594	2.572
Aluminum	SA	0.092	0.108	0.028	0.304	4.737	2.091	0.958	1.255	4.266	1.300	3.586
	SB	0.092	0.114	0.056	1.543	0.912	2.990	0.132	2.350	1.046	2.372	0.763

	DA	0.092	0.258	0.073	0.473	1.085	1.555	0.219	1.104	1.331	1.125	1.041
	DB	0.092	0.258	0.104	0.047	3.457	1.079	0.880	0.624	3.496	0.651	2.940
	DC	0.092	0.258	0.098	0.494	0.982	1.587	0.211	1.135	1.313	1.159	1.013
	DD	0.092	0.257	0.073	0.057	4.789	1.219	1.137	0.684	4.396	0.718	3.725
	TA	0.092	0.258	0.185	0.025	3.383	0.920	0.903	0.525	3.452	0.550	2.911
	TB	0.092	0.263	0.192	0.062	2.679	1.070	0.719	0.646	2.951	0.671	2.456
PVC	SA	0.092	0.085	0.027	0.181	5.302	1.760	1.114	1.018	4.645	1.054	3.951
	SB	0.092	0.085	0.054	1.239	0.975	2.643	0.141	2.028	1.150	2.050	0.848
	DA	0.092	0.060	0.071	0.397	1.132	1.446	0.246	1.012	1.390	1.030	1.095
	DB	0.092	0.060	0.102	0.033	3.599	0.995	0.929	0.568	3.598	0.594	3.035
	DC	0.092	0.060	0.096	0.381	1.226	1.463	0.270	1.013	1.488	1.033	1.179
	DD	0.092	0.060	0.071	0.042	4.956	1.138	1.189	0.628	4.510	0.660	3.833
	TA	0.092	0.077	0.182	0.019	3.469	0.875	0.933	0.493	3.513	0.517	2.969
	TB	0.092	0.070	0.186	0.049	2.751	1.020	0.746	0.610	3.005	0.635	2.509
Fiberglass	SA	0.092	0.051	0.027	0.194	4.961	1.773	1.096	1.041	4.525	1.093	3.770
	SB	0.092	0.051	0.055	1.276	0.922	2.656	0.139	2.050	1.121	2.080	0.810
	DA	0.092	0.050	0.076	0.422	1.120	1.488	0.236	1.046	1.373	1.064	1.080
	DB	0.092	0.050	0.103	0.039	3.536	1.029	0.907	0.592	3.553	0.619	2.993
	DC	0.092	0.050	0.107	0.409	1.202	1.504	0.258	1.049	1.462	1.069	1.154
	DD	0.092	0.072	0.070	0.037	5.012	1.114	1.206	0.610	4.548	0.637	3.868
	TA	0.092	0.069	0.185	0.020	3.449	0.885	0.926	0.500	3.499	0.525	2.955
	TB	0.092	0.071	0.188	0.051	2.740	1.027	0.742	0.615	2.997	0.640	2.501
Wood	SA	0.092	0.014	0.025	0.157	5.080	1.649	1.159	0.956	4.643	1.010	3.861
	SB	0.092	0.014	0.049	1.150	0.960	2.512	0.150	1.916	1.189	1.949	0.862
	DA	0.092	0.013	0.069	0.429	1.102	1.487	0.235	1.049	1.361	1.069	1.066
	DB	0.092	0.013	0.098	0.037	3.549	1.022	0.912	0.587	3.562	0.614	3.001
	DC	0.092	0.013	0.096	0.404	1.206	1.496	0.260	1.042	1.466	1.062	1.158
	DD	0.092	0.013	0.069	0.047	4.895	1.167	1.170	0.648	4.468	0.681	3.793
	TA	0.092	0.013	0.176	0.025	3.383	0.920	0.903	0.525	3.452	0.550	2.911
	TB	0.092	0.013	0.183	0.061	2.684	1.066	0.720	0.643	2.955	0.668	2.460

Ozone layer depletion [g (CFC)11 eq.]

Framing solution	Glazing solution	Opaque envelope	Framing	Glazing	Heating (South)	Cooling (South)	Heating (North)	Cooling (North)	Heating (West)	Cooling (West)	Heating (East)	Cooling (East)
No window		0.0243	0.0000	0.0000	0.0284	0.0011	0.0358	0.0003	0.0326	0.0011	0.0325	0.0011
No frame	SA	0.0199	0.0000	0.0015	0.0058	0.0987	0.0420	0.0207	0.0252	0.0901	0.0262	0.0751
	SB	0.0199	0.0000	0.0033	0.0305	0.0190	0.0602	0.0028	0.0471	0.0223	0.0476	0.0161
	DA	0.0199	0.0000	0.0050	0.0074	0.0245	0.0290	0.0055	0.0200	0.0299	0.0203	0.0237

	DB	0.0199	0.0000	0.0044	0.0005	0.0771	0.0199	0.0201	0.0112	0.0766	0.0118	0.0647
	DC	0.0199	0.0000	0.0075	0.0074	0.0262	0.0298	0.0059	0.0205	0.0317	0.0209	0.0252
	DD	0.0199	0.0000	0.0049	0.0013	0.0997	0.0258	0.0236	0.0145	0.0916	0.0152	0.0776
	TA	0.0199	0.0000	0.0061	0.0002	0.0762	0.0166	0.0207	0.0091	0.0760	0.0096	0.0645
	TB	0.0199	0.0000	0.0065	0.0008	0.0594	0.0202	0.0163	0.0119	0.0643	0.0124	0.0538
Aluminum	SA	0.0199	0.0040	0.0012	0.0064	0.0991	0.0438	0.0201	0.0263	0.0893	0.0272	0.0751
	SB	0.0199	0.0042	0.0027	0.0323	0.0191	0.0626	0.0028	0.0492	0.0219	0.0496	0.0160
	DA	0.0199	0.0112	0.0034	0.0099	0.0227	0.0326	0.0046	0.0231	0.0279	0.0235	0.0218
	DB	0.0199	0.0112	0.0029	0.0010	0.0724	0.0226	0.0184	0.0131	0.0732	0.0136	0.0615
	DC	0.0199	0.0112	0.0048	0.0103	0.0206	0.0332	0.0044	0.0238	0.0275	0.0243	0.0212
	DD	0.0199	0.0111	0.0038	0.0012	0.1002	0.0255	0.0238	0.0143	0.0920	0.0150	0.0780
	TA	0.0199	0.0141	0.0048	0.0005	0.0708	0.0193	0.0189	0.0110	0.0723	0.0115	0.0609
	TB	0.0199	0.0143	0.0052	0.0013	0.0561	0.0224	0.0150	0.0135	0.0618	0.0140	0.0514
PVC	SA	0.0199	0.0016	0.0012	0.0038	0.1110	0.0368	0.0233	0.0213	0.0972	0.0221	0.0827
	SB	0.0199	0.0016	0.0026	0.0259	0.0204	0.0553	0.0029	0.0424	0.0241	0.0429	0.0177
	DA	0.0199	0.0013	0.0033	0.0083	0.0237	0.0303	0.0051	0.0212	0.0291	0.0216	0.0229
	DB	0.0199	0.0013	0.0028	0.0007	0.0753	0.0208	0.0194	0.0119	0.0753	0.0124	0.0635
	DC	0.0199	0.0013	0.0047	0.0080	0.0257	0.0306	0.0056	0.0212	0.0312	0.0216	0.0247
	DD	0.0199	0.0013	0.0037	0.0009	0.1037	0.0238	0.0249	0.0131	0.0944	0.0138	0.0802
	TA	0.0199	0.0016	0.0047	0.0004	0.0726	0.0183	0.0195	0.0103	0.0735	0.0108	0.0621
	TB	0.0199	0.0014	0.0050	0.0010	0.0576	0.0213	0.0156	0.0128	0.0629	0.0133	0.0525
Fiberglass	SA	0.0199	0.0026	0.0012	0.0041	0.1038	0.0371	0.0229	0.0218	0.0947	0.0229	0.0789
	SB	0.0199	0.0025	0.0027	0.0267	0.0193	0.0556	0.0029	0.0429	0.0235	0.0435	0.0170
	DA	0.0199	0.0025	0.0035	0.0088	0.0234	0.0311	0.0049	0.0219	0.0287	0.0223	0.0226
	DB	0.0199	0.0025	0.0029	0.0008	0.0740	0.0215	0.0190	0.0124	0.0744	0.0130	0.0626
	DC	0.0199	0.0025	0.0053	0.0086	0.0251	0.0315	0.0054	0.0219	0.0306	0.0224	0.0241
	DD	0.0199	0.0036	0.0038	0.0008	0.1049	0.0233	0.0252	0.0128	0.0952	0.0133	0.0810
	TA	0.0199	0.0035	0.0048	0.0004	0.0722	0.0185	0.0194	0.0105	0.0732	0.0110	0.0619
	TB	0.0199	0.0036	0.0051	0.0011	0.0573	0.0215	0.0155	0.0129	0.0627	0.0134	0.0524
Wood	SA	0.0199	0.0011	0.0011	0.0033	0.1063	0.0345	0.0243	0.0200	0.0972	0.0211	0.0808
	SB	0.0199	0.0011	0.0024	0.0241	0.0201	0.0526	0.0031	0.0401	0.0249	0.0408	0.0180
	DA	0.0199	0.0011	0.0032	0.0090	0.0231	0.0311	0.0049	0.0219	0.0285	0.0224	0.0223
	DB	0.0199	0.0011	0.0026	0.0008	0.0743	0.0214	0.0191	0.0123	0.0746	0.0129	0.0628
	DC	0.0199	0.0011	0.0047	0.0085	0.0252	0.0313	0.0054	0.0218	0.0307	0.0222	0.0242
	DD	0.0199	0.0011	0.0037	0.0010	0.1024	0.0244	0.0245	0.0136	0.0935	0.0143	0.0794
	TA	0.0199	0.0010	0.0044	0.0005	0.0708	0.0193	0.0189	0.0110	0.0723	0.0115	0.0609
	TB	0.0199	0.0011	0.0048	0.0013	0.0562	0.0223	0.0151	0.0135	0.0618	0.0140	0.0515

Appendix III Environmental and cost life cycle approach to support selection of windows in early stages of building designs

This section comprises various figures presenting the structured under specification models for the attributes listed in Table 5.1.

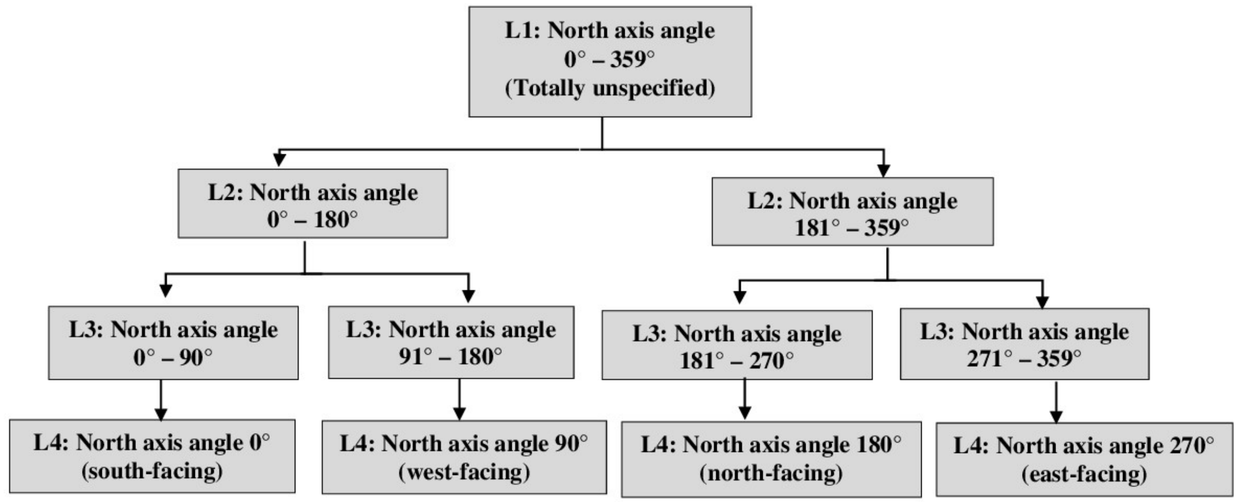

Figure A. 2 The structured under specification model for orientation (North axis angle: the angle of the entire building compared to true North)

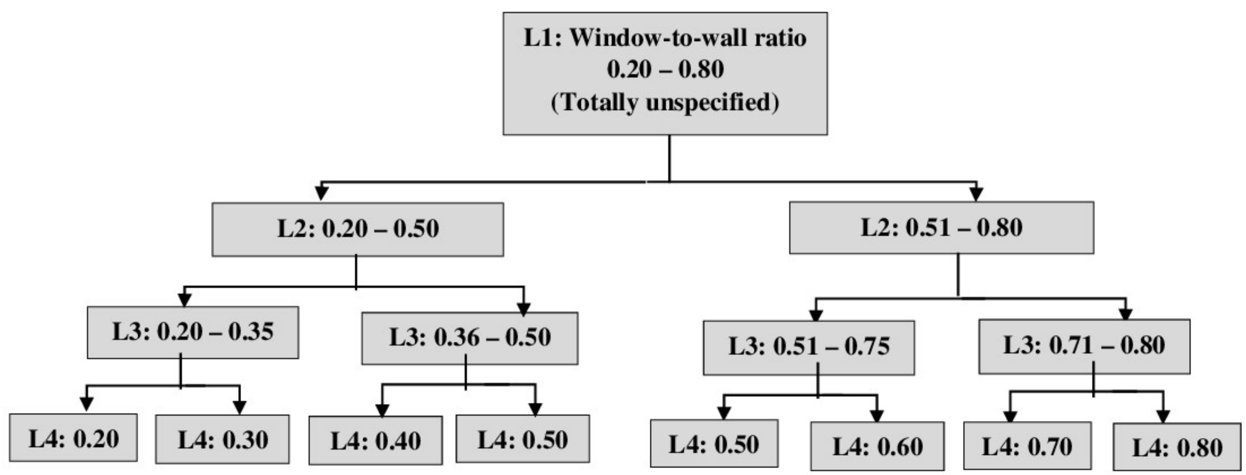

Figure A. 3 The structured under specification model for window-to-wall ratio

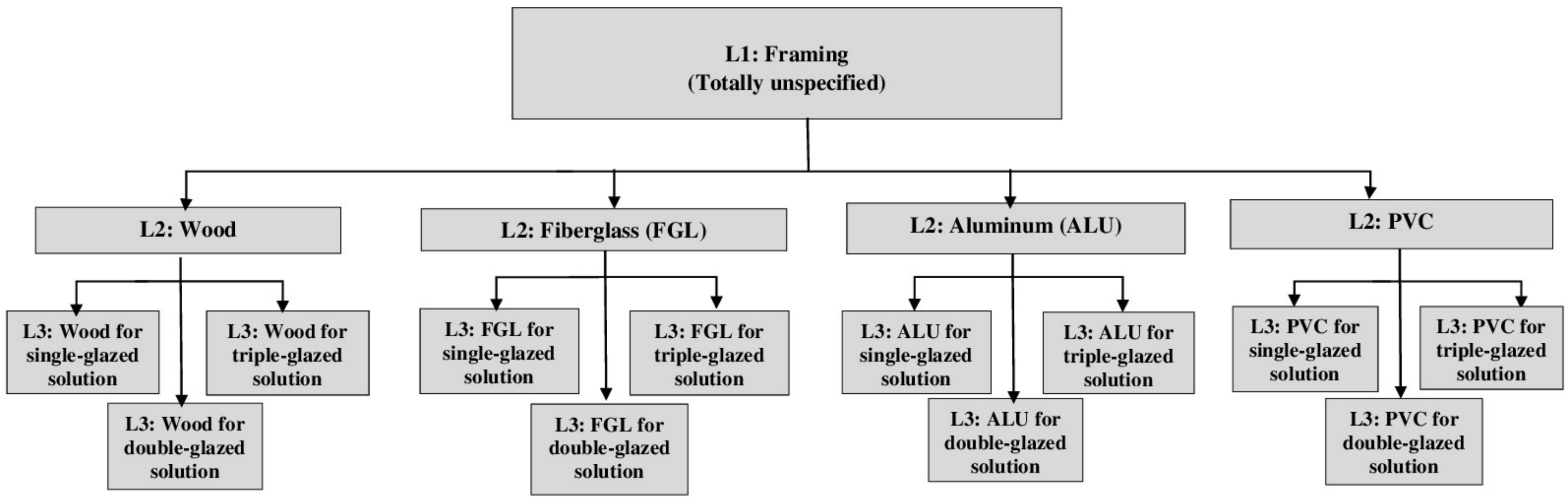

Figure A. 4 The structured under specification model for framing material

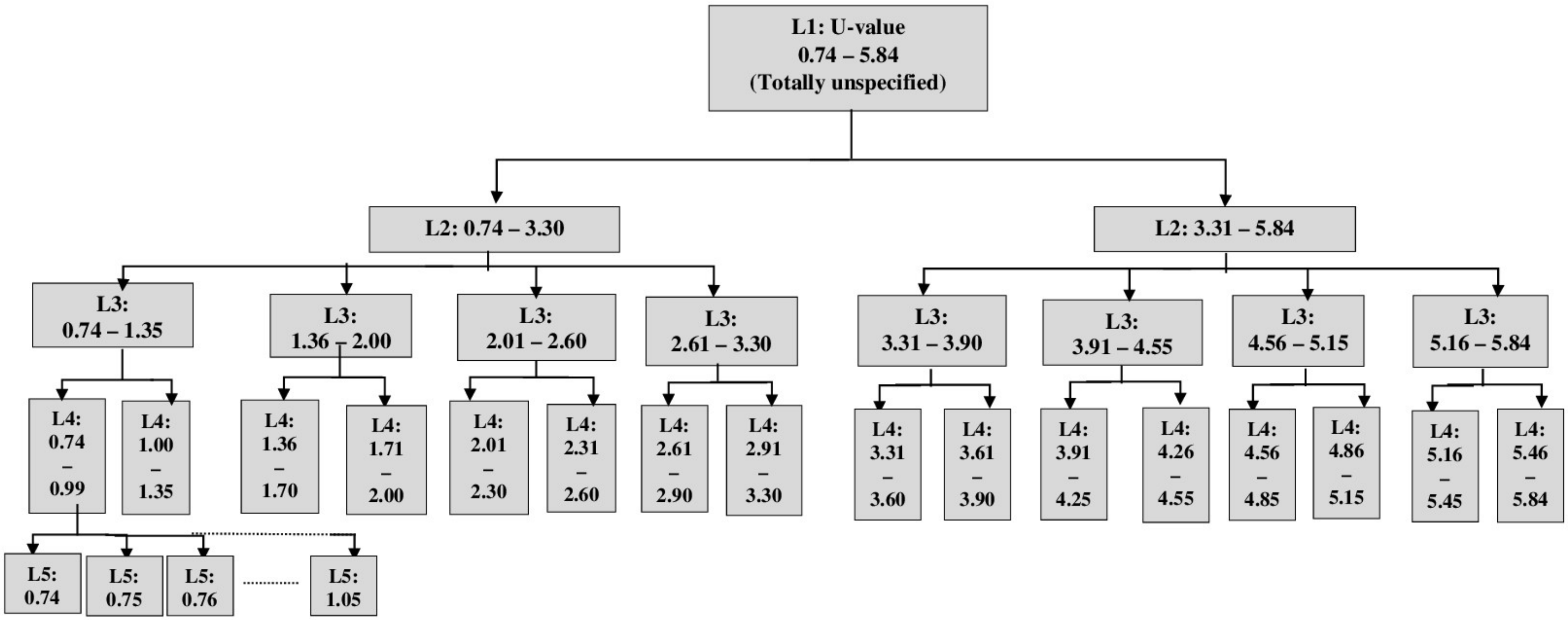

Figure A. 5 The structured under specification model for thermal transmittance value (U-value in W/(m^{2}K))

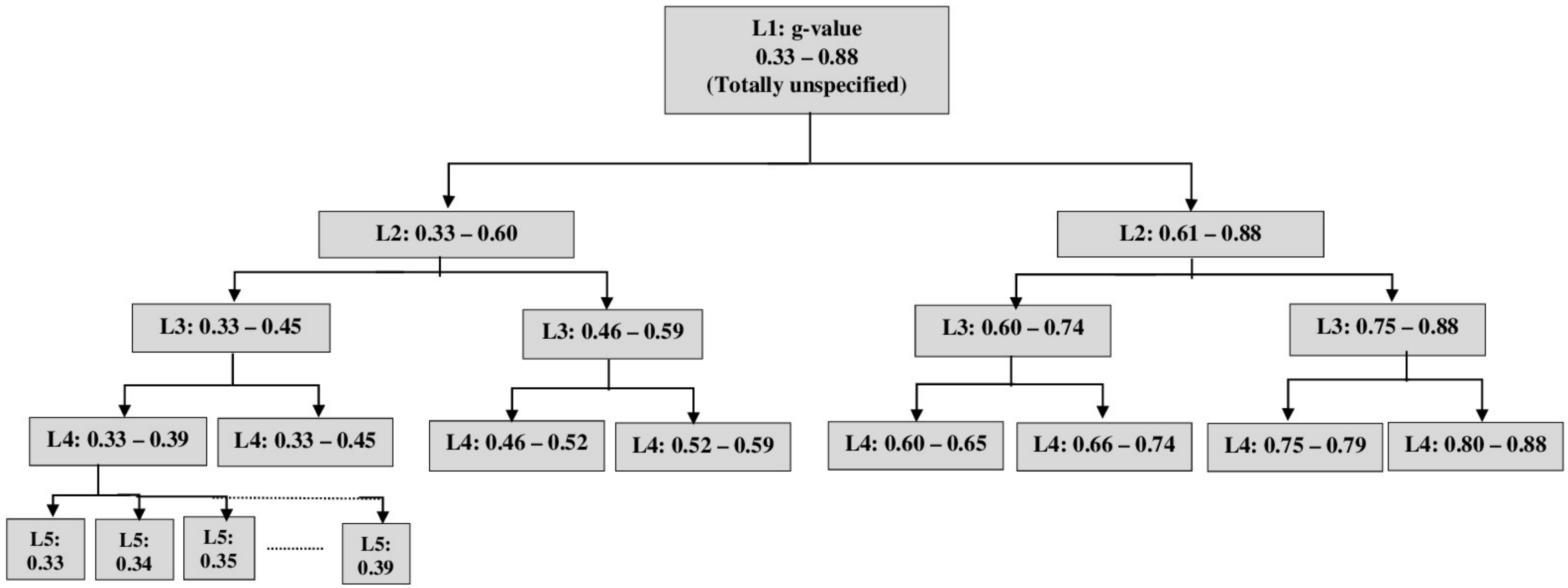

Figure A. 6 The structured under specification model for solar factor (g-value)

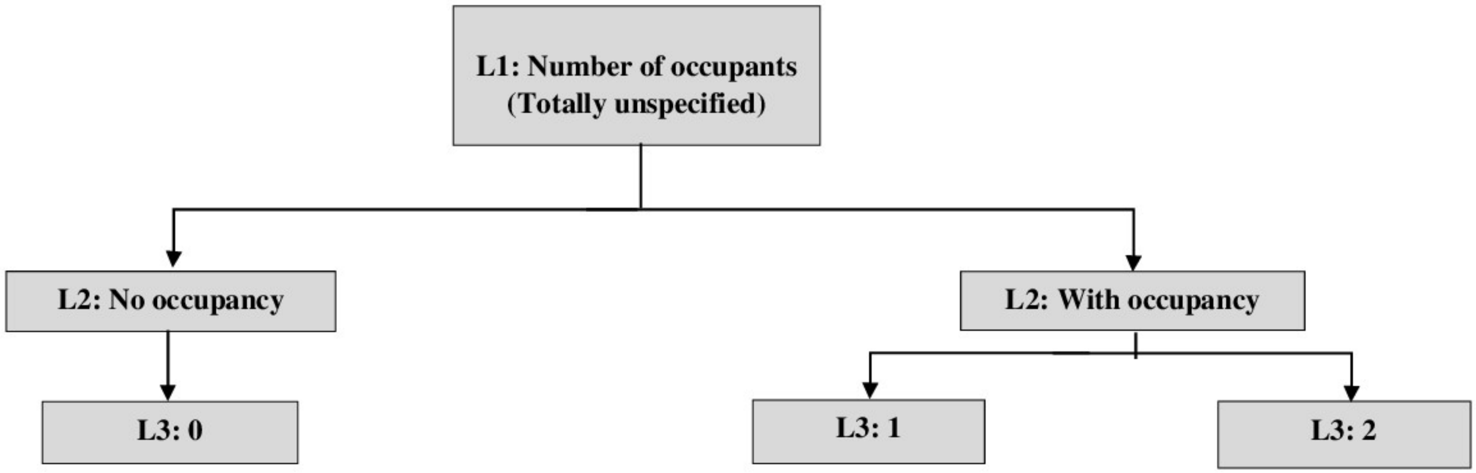

Figure A. 7 The structured under specification model for number of occupants

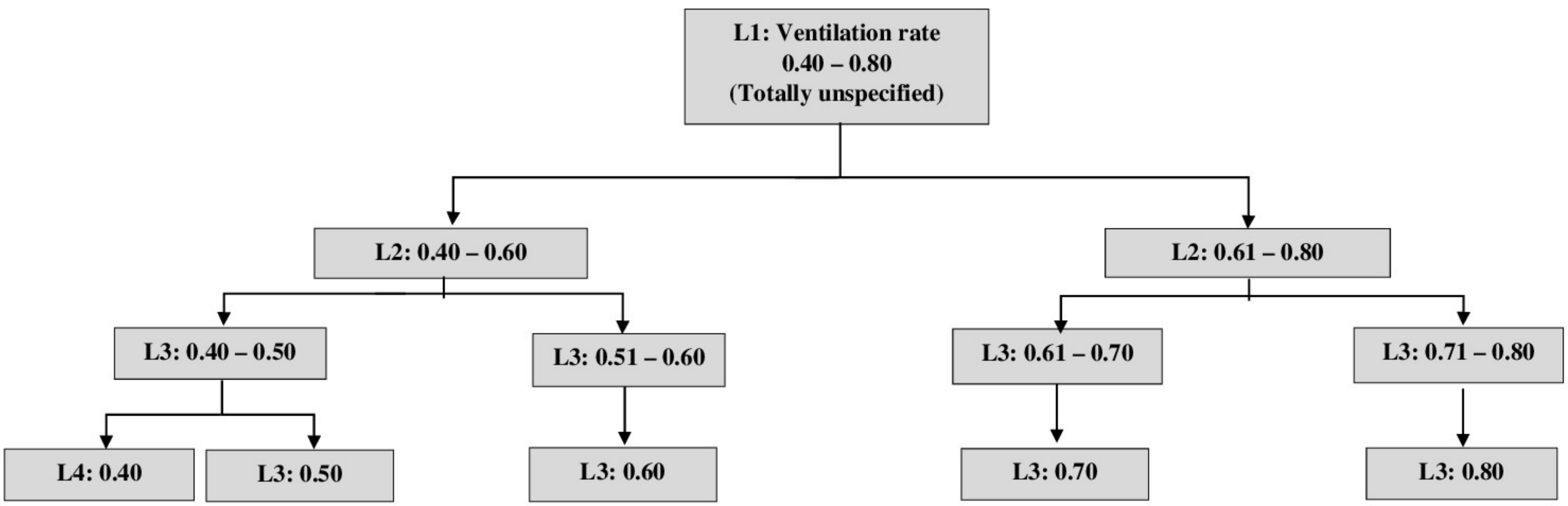

Figure A. 8 The structured under specification model for ventilation rate (h^{-1})