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Developing a decision-making framework for resolving conflicts when selecting windows and blinds

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ABSTRACT

Windows and blinds play a significant role in both shaping energy consumption and enhancing indoor comfort. But there are still difficulties with selecting windows and blinds due to the existence of potential conflicts between visual comfort, thermal comfort, energy consumption and life-cycle cost. A literature review was conducted with the purpose of developing a decision-making framework that resolves the conflicts, and allows selecting a window and blind design based on trade-off between visual comfort, thermal comfort, energy consumption and life-cycle cost. The decision-making framework was developed by integrating non-dominated sorting genetic algorithm-II as an optimization algorithm with analytical hierarchy process as a multi-criteria decision-making method. The optimization algorithm considers different window and blind design variables and analyses multiple designs, while the multi-criteria decision-making method ranks the optimization results and selects a trade-off design. An operating package enabled the decision-making framework to be automated. The operating package was obtained by coupling EnergyPlus as a simulation tool and modeFRONTIER as an integration platform. The decision-making framework was developed to select a trade-off window and blind design through intelligent use of simulation in analysing big-data in built environment, energy and cost sectors. Application of the framework ensures the minimum visual and thermal comfort thresholds with the lowest energy demand and cost. Architects and designers can use the framework during the design or renovation phase of residential and commercial buildings.

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Trade-off design; big-data; optimization; multi-criteria decision-making; non-dominated genetic algorithm II; framework design; analytical hierarchy process

Introduction

The latest version of the EU Energy Performance of Buildings Directive (EPBD) demands that all new buildings constructed in EU countries must be nearly zero-energy by the end of 2020 (EPBD, 2010). Furthermore, the subsequent annex to the EPBD known as COM (2016) 765 final has stated that energy demand should be calculated to ensure minimum comfort thresholds, defined at national levels (EPBD, 2016). At this point, windows play an important role in both shaping the energy performance of buildings and enhancing indoor comfort (Nikoofard, Ugursal, & Beausoleil-Morrison, 2014). During cold seasons, windows can increase the total heat demand due to heat loss through transmission, but they can also help to reduce heat demand by means of penetrating solar heat

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(Avasoo, 2007; Nikoofard et al., 2014). During warm seasons, windows can be a main source of overheating that increases the overall demand for cooling (Nikoofard et al., 2014). Furthermore, windows have an important part to play in improving visual comfort and enhancing well-being by generating feelings of pleasure also by boosting individuals' ability to perform cognitive interpretations (Heerwagen, 1998, 2000; Krieger & Higgins, 2002; Veitch, 2001). For instance, providing daylight can help to create feelings of pleasure, including happiness, calmness and a sense of safety (Boyce, Hunter, & Howlett, 2003) and vitality (Boubekri et al., 2014). In addition, providing daylight decreases stress levels (Boyce et al., 2003) and improves individuals' ability to perform cognitive interpretations (Aries, Aarts, & van Hoof, 2015; Boyce et al., 2003).

According to Mangkuto, Rohmah, and Asri (2016), the benefits of daylight and its role in enhancing well-being may present a strong case in favour of larger window areas for increasing the amount of daylight entering buildings. However, larger windows increase the risk of overheating and glare, (Al horr et al., 2016; Lee & Tavil, 2007; Taylor, Watkins, Marshall, Dascombe, & Foster, 2014) which may have an adverse impact on cognitive interpretations (Al horr et al., 2016; Zhang & Dear, 2017). Architects and designers may intend to use blinds to control solar gain, thereby reduce overheating and glare problems (Avasoo, 2007; Lee & Tavil, 2007). But larger windows in combination with blinds increase the life cycle cost (LCC) for owners by increasing the energy consumption and the cost of investment (O'Brien, Kapsis, & Athienitis, 2013) and maintenance (Nikoofard et al., 2014).

The contradictory effects of the window and blind selection and the availability of diverse options makes a selection of windows and blinds a rather complicated, multidimensional problem. The available[1] building performance simulation tools can evaluate the various effects of windows and blinds on visual comfort, thermal comfort, total energy consumption and LCC. However, these simulation tools support the selection of windows and blinds based mostly on a single criterion, but not on several criteria, where there is a trend to find a trade-off between criteria. Furthermore, making decisions, which rely on meeting a single criterion, are not recommended (Monghasemi, Nikoo, Fasaee, & Adamowski, 2015). At this point, Mattiussi, Rosano, and Simeoni (2014) discusses about two methods, which permit a trade-off between reducing total energy consumption and cost and meeting occupants' preferences for visual and thermal comfort; including multi-criteria decision-making (MCDM) and optimization.

Multi-criteria decision-making (MCDM) involves multiple design solutions and attempts to select a trade-off solution based on decision-makers' preferences. MCDM methods assist decision-makers with establishing direct verbal communication (Peniwati, 2007), which helps to transfer their preferences into a decision-making process (Harputlugil, Prins, Gültekin, & Topçu, 2011; Triantaphyllou & Mann, 1995). Consequently, a MCDM method helps decision-makers to make efficient decisions and choose a solution from the solutions available (Mosavi, 2010). One of the main limitations with MCDM methods is the feasibility of analysing a large number of solutions (Mosavi, 2010). This means that a MCDM method is applicable within a limited number of design solutions when selecting the windows and blinds. Multiple MCDM methods have been developed and introduced for resolving a variety of decision-making problems (Peniwati, 2007). In the context of the window and blind design, Jalilzadehazhari, Johansson, Johansson, and Mahapatra (2017) employed a MCDM method to select a trade-off interior blind, based on trade-off between visual comfort, thermal comfort, energy consumption and LCC. The trade-off blind was selected among 40 different interior blinds.

Optimization is the other method used often in selecting windows and blinds. Earlier studies used an algorithm to analyse big-data and resolve an optimization problem with no more than three objectives (Carlucci, Cattarin, Causone, & Pagliano, 2015b; Manzan & Padovan, 2015; Vera, Uribe, Bustamante, & Molina, 2016). Because, optimization algorithms are ineffective in solving an optimization problem with more than three objectives and cannot present a single trade-off solution (Chand & Wagner, 2015; Farina & Amato, 2003). Thus, using solely an optimization algorithm is insufficient for selecting a window and blind design based on trade-off between visual comfort, thermal comfort, total energy consumption and LCC.

According to Hadas and Nahum (2016), the integration of an optimization algorithm with a MCDM method helps to resolve an optimization problem with more than three objectives. The integration allows an optimization algorithm to consider different window and blind design variables and analyses multiple window and blind designs. Then a MCDM method ranks optimization results and presents a trade-off design. Integrating an optimization algorithm with a MCDM method has been accomplished in building design practices (Monghasemi et al., 2015), but no study has applied this integration to the selection of windows and blinds. According to Shi, Tian, Chen, Si, and Jin (2016), the earlier attempt in integrating an optimization algorithm with a MCDM method is to specify an operating package, which allows the integration to be automated. Accordingly, this paper aims; (i) to specify an operating package and (ii) to develop a decision-making framework by integrating an optimization algorithm with an MCDM method, which is operable by using the operating package. The decision-making framework is a novel response to the lack of a feasible method (Norouzi, Shabak, Embi, & Khan, 2015) for selecting a window and blind design based on a trade-off between visual comfort, thermal comfort, energy consumption and life-cycle cost.

Method

A literature review was conducted to specify an operating package and to develop a decision-making framework. The search for relevant studies was carried out using the Scopus database and limited to English-language publications. The initial search terms are shown in Table 1. Each search term was limited so that only studies published between 2001 and 2017 were identified. Furthermore, the subject areas were limited to engineering, energy, environmental science, economics, econometrics and finance, computer science and mathematics. The found studies were later limited to the published journal papers, conference papers, reviews and book chapters. Further limitations were applied as 32 keywords were excluded from the search, including Roofs, Skylight, Solar Power Generation, Solar Radiation, Photovoltaic Effects, Photovoltaic System, Carbon Emission, Climate Change, Roof, Semi-transparent Photovoltaic, Renewable Energy Resources, Atmospheric Temperature, Atrium, CO Mitigation 2, Carbon Credit, Carbon Dioxide, Carbon Emissions, Ecosystems, Physiology, Scan-to-BIM, 3-D Printing, 3D Printers, 3D Printing, Age Estimation, Age-Related Macular Degeneration (AMD), Age-related Macular Degeneration, Ageing Population, Air Conditioning, Air Leakage, Animal, Animals, Animalia. A total of 287 studies were then found. The abstracts of the studies were read, and the relevant 105 studies were selected for further analysis. Additional studies cited as references by the 105 eligible studies were also read to gain in-depth knowledge.

Figure 1 shows the procedure applied in selecting an operating package and in developing the decision-making framework. The first step was to determine the operating package which allows automating an integration between an optimization algorithm and a MCDM method. The integration process follows the main three phases introduced by Mosavi (2010): pre-processing, optimization and post-processing phases. The results were then synthesized to develop the decision-making framework.

Operating packages for establishing integration

Establishing an integration between an optimization algorithm and a MCDM method in practice requires an operating package, which allows the integration to be automated (Shi et al., 2016).

Table 1. The initial search terms in Scopus.

	Search term	Found studies	Eligible after pre-selection
Scopus	(visual comfort OR light quality OR thermal comfort OR energy consumption OR life cycle cost) AND (window OR blind OR shading)	131	33
Scopus	(visual comfort OR light quality OR thermal comfort OR energy consumption OR life cycle cost) AND (window OR blind OR shading) AND (optimization)	94	60
Scopus	(visual comfort OR light quality OR thermal comfort OR energy consumption OR life cycle cost) AND (window OR blind OR shading) AND (decision-making)	62	12

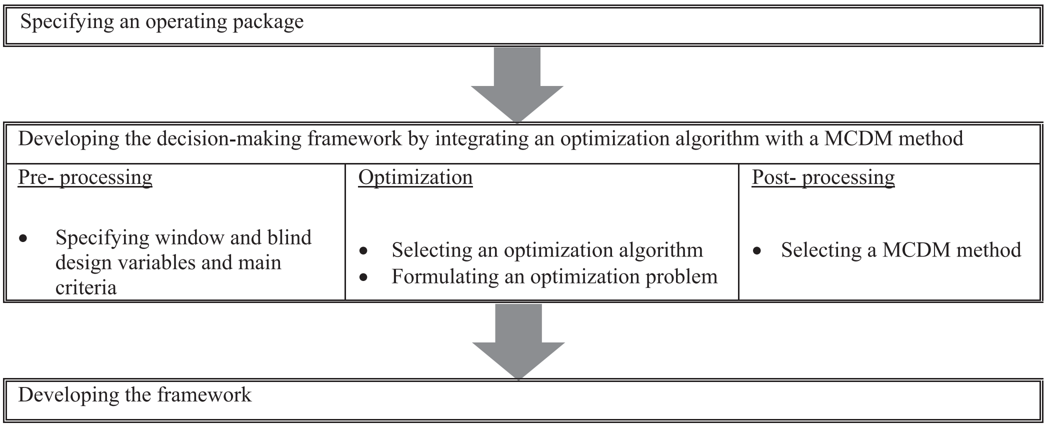

Figure 1. The procedure applied in developing a decision-making framework.

According to Shi et al. (2016), the most powerful operating package can be obtained by coupling a building performance simulation tool into an integration platform. A simulation tool allows developing an initial room or building design, while an integration platform provides possibilities to run an optimization and use a MCDM method to select a trade-off design. To obtain a powerful operating package, the utilization of different simulation tools was studied (Figure 2). Among all 105 investigated studies, 34% of them analysed the performance of various window and blind designs with respect to visual comfort. Figure 2 shows that Radiance and EnergyPlus simulation tools have

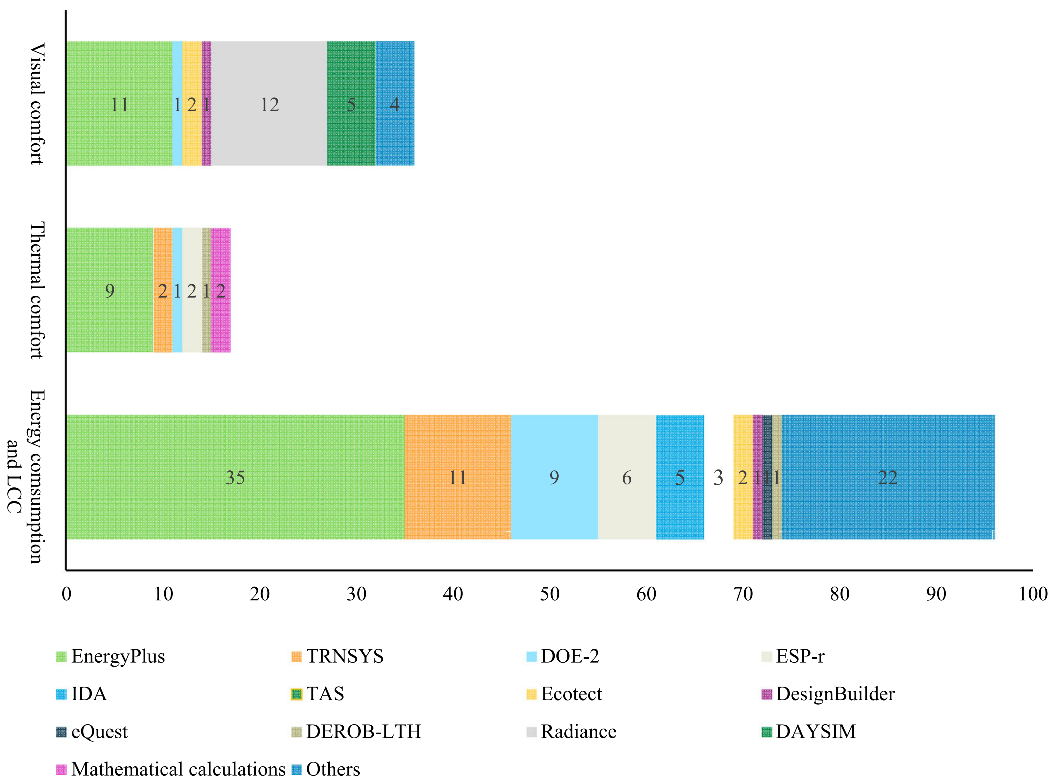

Figure 2. The utilization of different simulation tools.

mostly used by earlier studies for evaluating visual comfort. Moreover, about 16% of the investigated studies analysed the performance of various window and blind designs with respect to thermal comfort, while 90% of them focused on energy consumption and LCC. At this point, EnergyPlus was the most frequently used simulation tool for evaluating thermal comfort, energy consumption and LCC.

A possible explanation for the high utilization of EnergyPlus can be the text-based format of this simulation tool, which facilitates the coupling process with an integration platform (Nguyen, Reiter, & Rigo, 2014). Furthermore, EnergyPlus is validated as a point of comparative and analytical tests (Carlucci et al., 2015b). Comparative tests are carried out according to ANSI/ASHRAE 140 and the IEA SHC Task34/Annex43 BESTest method, while analytical tests are performed according to ASHRAE Research Projects 865 and 1052 (Carlucci et al., 2015b).

Among the available integration platforms, modelCenter and modeFRONTIER enable to automate an integration between an optimization algorithm and a MCDM method (Shi et al., 2016). The abovementioned integration platforms allow users to run an optimization and to use a MCDM method to rank the optimization results and thereby to select a trade-off design (Shi et al., 2016). The other advantages of using the abovementioned integration platforms is their flexibility in coupling with a simulation tool (Shi et al., 2016). Lee, Trcka, and Hensen (2014) used the modeFRONTIER to minimize the total energy consumption in an industrial building. In a similar study, Shi (2011) used the modeFRONTIER to minimize energy need for space conditioning. Flager, Welle, Bansal, Soremekun, and Haymaker (2009) used the modelCenter to minimize the total energy consumption in an educational building. No study was found for a detailed comparison between ModelCenter and modeFRONTIER, but Attia, Hamdy, O'Brien, and Carlucci (2013) recommended modeFRONTIER, when running an optimization.

To obtain an operating package, EnergyPlus was selected to be coupled to modeFRONTIER. This decision was made because EnergyPlus is one of the most complete and eligible simulation tools (Sousa, 2012), which allows users to evaluate visual comfort, thermal comfort, energy consumption and LCC simultaneously. Furthermore, modeFRONTIER was selected due to its various capabilities in running an optimization. ModeFRONTIER can handle optimization constraints automatically, furthermore, it handles both continues and discrete variables (Palonen, Hamdy, & Hasan, 2013)

To couple EnergyPlus with modeFRONTIER a script should be written either in DOSBatch file node[2] or EasyDriver node in modeFRONTIER. DOSBatch file and EasyDriver allow users to run EnergyPlus via modeFRONTIER. Once the coupling process was successfully accomplished, an initial model of a room or a building should be developed in EnergyPlus. Later, the performance of the model with respect to visual comfort, thermal comfort, energy consumption and LCC should be evaluated. The outputs of EnergyPlus will be transferred to an optimization algorithm in modeFRONTIER. Then, the optimization algorithm changes the value of design variables to generate new population of models and iterates the simulation process. The iteration process will be pursued until the maximum number of populations is achieved. When the optimization process is terminated, a MCDM method is used to rank the optimization results and to select a trade-off window and blind design. Figure 3 shows a simplified illustration of the coupling process between EnergyPlus and modeFRONTIER.

Pre-processing phase

The pre-processing phase determines window and blind design variables and identifies the main criteria of visual comfort, thermal comfort, energy consumption and LCC. Around 52% of the investigated studies (52% of the 105 eligible studies) analyse the effects of different window and blind design variables on visual comfort, thermal comfort, energy consumption and LCC *without performing an optimization*. The abovementioned studies developed mainly a limited number of designs and analysed how changing window and blind design variables affect visual comfort, thermal comfort, energy consumption or LCC. About 14% of the investigated studies performed an optimization *by*

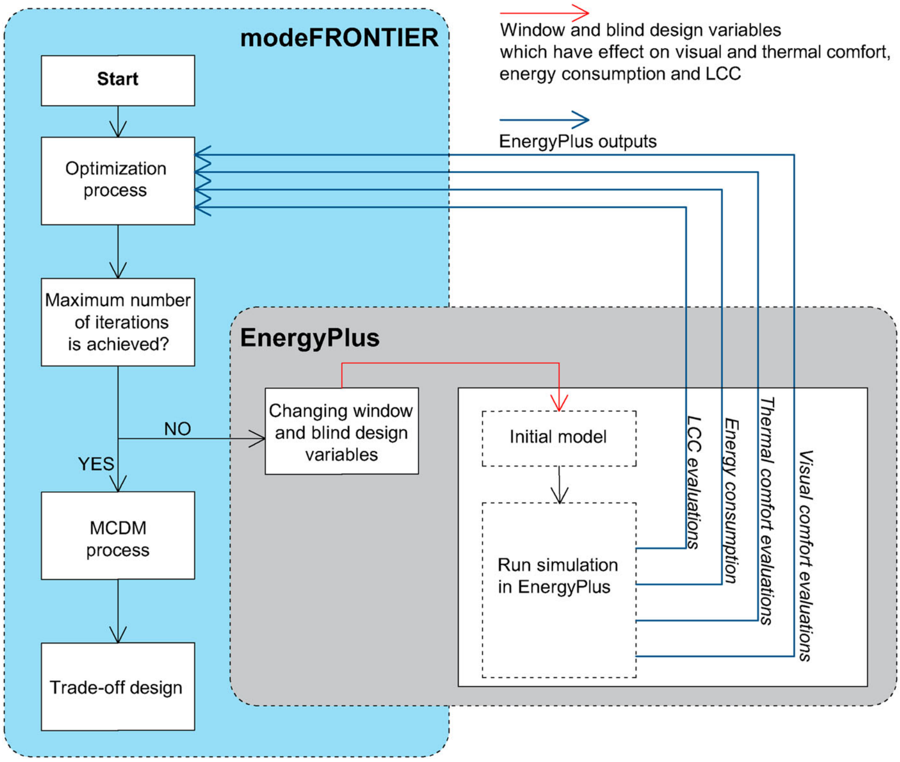

Figure 3. Simplified illustration of the coupling process between EnergyPlus and modeFRONTIER.

concentrating only on window and blind design variables. The aim of these studies was to find the best window and blind design with respect to optimization objectives, including visual comfort, thermal comfort, energy consumption or LCC. Around 29% of the investigated studies carried out an optimization by *focusing on overall building performance* rather than just window and blind design variables. The optimization process within the abovementioned studies comprised the evaluation of heating, ventilation and air condition system, building envelopes, building geometries, occupancy schedule and operation schedule. Furthermore, some of the studies among the latest group compared the effectiveness of optimization algorithms in solving different optimization problems. Finally, around 5% of the investigated studies provided an overview regarding available optimization algorithms and explained various steps required for running an optimization and also introduced and compared various MCDM methods.

Tables 2 and 3 summarize the window and blind design variables, specified in the investigated studies. Furthermore, the tables present the main criteria of visual comfort, thermal comfort, energy consumption and LCC in conjunction with window and blind selection. The main visual comfort criteria, frequently analysed by investigated studies, comprise the amount of light, glare and uniformity. However, only one study, among all 105 investigated studies, analysed the light intensity distribution of an external overhang panel (Tsangrassoulis et al., 2006). With respect to thermal comfort, investigated studies concentrated mainly on the effects of the window and blind designs on Fanger's thermal comfort model, long percentage dissatisfied and temperature. Considering energy consumption, total energy consumption, the energy needed for space heating, cooling also the electricity needed for lighting and artificial ventilation were frequently analysed. Finally, with respect to LCC, the investigated studies analysed the investment, consumption and maintenance costs of various window and blind designs.

Table 2. Window and blind design variables and main criteria for evaluating visual and thermal comfort.

Design variables		Visual comfort: Amount of light	Visual comfort: Glare	Visual comfort: Uniformity	Visual comfort: Light intensity distribution	Thermal comfort: Fanger's thermal comfort model	Thermal comfort: Long-term percentage dissatisfaction	Thermal comfort: Temperature
Window design variable	Window size (width and length of window)	Futrell, Ozelkan, and Brentrup (2015), Ochoa, Aries, van Loenen, and Hensen (2012), Singh, Lazarus, and Kishore (2015), Acosta, Munoz, Campano, and Navarro (2015), Gagne and Andersen (2012), Torres and Sakamoto (2007)	Lee and Tavil (2007), Ochoa et al. (2012), Singh et al. (2015), Mainini, Bonato, Poli, and Speroni (2015), Atzeri, Cappelletti, Gasparella, and Tzempelikos (2013), Gagne and Andersen (2012)	Ochoa et al. (2012), Suga, Kato, and Hiyama (2010)		Atzeri, Pernigotto, Cappelletti, Gasparella, and Tzempelikos (2013), Wang, Nyuk, and Li (2007), Mainini et al. (2015), Atzeri, Cappelletti, et al. (2013), Wang et al. (2007)		Suga et al. (2010), Wang et al. (2007), *Al-Homoud (2005, 2009)
	Orientation	Carlucci et al. (2015b), Singh et al. (2015)	Carlucci et al. (2015b), Singh et al. (2015), Atzeri, Cappelletti, et al. (2013)			Atzeri, Pernigotto, et al. (2013), Wang et al. (2007), Atzeri, Cappelletti, et al. (2013), Wang et al. (2007)	Carlucci et al. (2015b)	Wang et al. (2007)
	Window position and form	Acosta et al. (2015), Gagne and Andersen (2012)	Lee and Tavil (2007), Gagne and Andersen (2012)					
	Glazing system	Futrell et al. (2015), Fasi and Budaiwi (2015), Singh et al. (2015), Chien and Tseng (2014), Liang, Wu, and Wilson (2015), Torres and Sakamoto (2007)	Lee and Tavil (2007), Fasi and Budaiwi (2015), Singh et al. (2015), Mainini et al. (2015), Atzeri, Cappelletti, et al. (2013)	Suga et al. (2010)		Atzeri, Pernigotto, et al. (2013), Mainini et al. (2015), Atzeri, Cappelletti, et al. (2013), Griego, Krarti, and Hernández-Guerrero (2012)	Liang et al. (2015)	Suga et al. (2010), *Al-Homoud (2005), Al-Homoud (2009)
External venetian	Number of louvers	González and Fiorito (2015)		González and Fiorito (2015)				
	Width of louver	González and Fiorito (2015)		González and Fiorito (2015)				
	Slope angle of louver	González and Fiorito (2015), De Carli and De Valeria (2009)		González and Fiorito (2015)				
	Material properties					Atzeri, Pernigotto, et al. (2013)		
External overhang	Length of panel**	Futrell et al. (2015), Chien and Tseng (2014), Gagne and Andersen (2012)	Gagne and Andersen (2012)			Wang et al. (2007)		Wang et al. (2007)

(Continued)

Table 2. Continued.

Design variables		Visual comfort				Thermal comfort		
		Amount of light	Glare	Uniformity	Light intensity distribution	Fanger's thermal comfort model	Long-term percentage dissatisfaction	Temperature
	Slope angle of panel				Tsangrassoulis, Bourdakis, Geros, and Santamouris (2006)			
	Width of panel	De Carli and De Valeria (2009), Torres and Sakamoto (2007)						
	Material properties	Torres and Sakamoto (2007)						
Interior overhang	Width of panel	Chien and Tseng (2014), De Carli and De Valeria (2009), Torres and Sakamoto (2007)						
	Material properties	Torres and Sakamoto (2007)						
External vertical fins	Width of fins	Torres and Sakamoto (2007)						
	Material properties	Torres and Sakamoto (2007)						
External roller	Material properties		Atzeri, Cappelletti, et al. (2013)			Atzeri, Pernigotto, et al. (2013), Atzeri, Cappelletti, et al. (2013)		
Internal venetian	Slope angle of louver	Chan and Tzempelikos (2015), Shin, Kim, and Kim (2013), Ahmad, Monjur, Hippolyte, Rezgui, and Li (2015)	Oh, Lee, and Yoon (2013), Shin et al. (2013)	Ahmad et al. (2015)		Chaiyapinunt and Khamporn (2014)		
	Material properties	Chan and Tzempelikos (2015)						
	Height of blind	Shin et al. (2013)	Shin et al. (2013)					
Internal roller	Material properties	Yoon, Jeong, and Lee (2014), Chan and Tzempelikos (2015), Singh et al. (2015)	Singh et al. (2015)					

*Operative temperature.
**The length of a panel comprises mainly the window's length plus left and right extensions of the panel from the window.

Table 3. Window and blind design variables and main criteria for evaluating energy consumption and LCC.

Design variables		Energy consumption kWh/m²					LCC		
		Heating	Cooling	EI for lighting	Total energy demand	Artificial ventilation	Investment	Consumption	Maintenance
Window design variable	Window size (width and length of window)	Atzeri, Pernigotto, et al. (2013), Wetter and Wright (2003), Ochoa et al. (2012), Singh et al. (2015), Atzeri, Cappelletti, et al. (2013), Wright and Mourshed (2009), Gong, Akashi, and Sumiyoshi (2012), Wang, Gwilliam, and Jones (2009), Persson, Roos, and Wall (2006), Eskin and Türkmen (2008), Susorova, Tabibzadeh, Rahman, Clack, and Elnimeiri (2013), Gratia and De Herde (2003), Leskovar and Premrov (2011), Gasparella, Pernigotto, Cappelletti, Romagnoni, and Baggio (2011), Jaber and Ajib (2011b), Poirazis, Blomsterberg, and Wall (2008), Jaber and Ajib (2011a), Ruiz and Romero (2011)	Atzeri, Pernigotto, et al. (2013), Wetter and Wright (2003), Ochoa et al. (2012), Singh et al. (2015), Atzeri, Cappelletti, et al. (2013), Zemella, De March, Borrotti, and Poli (2011), Wright and Mourshed (2009), Yıldız and Arsan (2011), Gong et al. (2012), Tsikaloudaki, Laskos, Theodosiou, and Bikas (2012), Gratia, Bruyere, and De Herde (2004), Cheung, Fuller, and Luther (2005), Persson et al. (2006), Eskin and Türkmen (2008), Susorova et al. (2013), Ratti, Baker, and Steemers (2005), Gratia and De Herde (2003), Leskovar and Premrov (2011), Inanici and Demirbilek (2000), Gasparella et al. (2011), Jaber and Ajib (2011b), Poirazis et al. (2008), Jaber and Ajib (2011a), Ruiz and Romero (2011)	Acosta et al. (2015), Atzeri, Pernigotto, et al. (2013), Wetter and Wright (2003), Ochoa et al. (2012), Singh et al. (2015), Atzeri, Cappelletti, et al. (2013), Suga et al. (2010), Zemella et al. (2011), Wright and Mourshed (2009), Poirazis et al. (2008)	Kim, Kim, Kim, and Cho (2014), Lee and Tavil (2007), Znouda, Ghrab-Morcos, and Hadj-Alouane (2007), Singh et al. (2015), *Mainini et al. (2015), Hassouneh, Alshboul, and Al-Salaymeh (2010), Tuhus-Dubrow and Krarti (2010), Laouadi, Atif, and Galasiu (2002), Jaber and Ajib (2011a), Ruiz and Romero (2011), **Ihm and Krarti (2012), Al-Homoud (2005), Al-Homoud (2009), Caldas and Norford (2002)	Wetter and Wright (2003), Ochoa et al. (2012), Singh et al. (2015), Suga et al. (2010), Poirazis et al. (2008)	Znouda et al. (2007), Mainini et al. (2015), Suga et al. (2010), Charron (2008), Tuhus-Dubrow and Krarti (2010), Wang, Rivard, and Zmeureanu (2005), Wang, Rivard, and Zmeureanu (2006), Wang, Zmeureanu, and Rivard (2005), Bichiou and Krarti (2011), Ouarghi and Krarti (2006), Jaber and Ajib (2011a), **Ihm and Krarti (2012)	Znouda et al. (2007), Mainini et al. (2015), Tuhus-Dubrow and Krarti (2010), Wang, Rivard, et al. (2005), Wang et al. (2006), Wang, Zmeureanu, et al. (2005), Bichiou and Krarti (2011), Ouarghi and Krarti (2006), Jaber and Ajib (2011a), Ruiz and Romero (2011), **Ihm and Krarti (2012)	Znouda et al. (2007), Mainini et al. (2015)
	Orientation	Atzeri, Pernigotto, et al. (2013), Wetter and Wright (2003), Singh et al. (2015), Gong et al. (2012), Wang et al. (2009), Persson et al. (2006), Susorova et al. (2013), Leskovar and Premrov (2011), Palmero-Marrero and Oliveira (2010), Gasparella et al. (2011), Jaber and Ajib (2011b), Ruiz and Romero (2011)	Atzeri, Pernigotto, et al. (2013), Wetter and Wright (2003), Singh et al. (2015), Yıldız and Arsan (2011), Gong et al. (2012), Tsikaloudaki et al. (2012), Hammad and Abu-Hijleh (2010), Chua and Kiang (2010), Florides, Kalogirou, and Wrobel (2002), Capeluto (2003), Persson et al. (2006), Susorova et al. (2013), Leskovar and Premrov (2011), Palmero-Marrero and Oliveira (2010), Gasparella et al. (2011), Jaber and Ajib (2011b), Ruiz and Romero (2011)	Atzeri, Pernigotto, et al. (2013), Wetter and Wright (2003), Singh et al. (2015), Capeluto (2003)	Kim et al. (2014), Singh et al. (2015), Hassouneh et al. (2010), Tuhus-Dubrow and Krarti (2010), Ruiz and Romero (2011), **Ihm and Krarti (2012)	Wetter and Wright (2003), Singh et al. (2015)	Charron (2008), Tuhus-Dubrow and Krarti (2010), Wang, Rivard, et al. (2005), Wang, Zmeureanu, et al. (2005), Bichiou and Krarti (2011), Chua and Kiang (2010), Florides et al. (2002), **Ihm and Krarti (2012)	Tuhus-Dubrow and Krarti (2010), Wang, Rivard, et al. (2005), Wang, Zmeureanu, et al. (2005), Bichiou and Krarti (2011), Chua and Kiang (2010), Florides et al. (2002), Ruiz and Romero (2011), **Ihm and Krarti (2012)	Chua and Kiang (2010)
	Window position and form	Wright and Mourshed (2009)	Wright and Mourshed (2009), Gratia et al. (2004)	Acosta et al. (2015), Wright and Mourshed (2009)	*Lee and Tavil (2007), *Kämpf, Wetter, and Robinson				

(Continued)

Table 3. Continued.

Design variables		Energy consumption kWh/m^2					LCC		
		Heating	Cooling	El for lighting	Total energy demand	Artificial ventilation	Investment	Consumption	Maintenance
					(2010), Caldas and Norford (2002)				
	Glazing system	Atzeri, Pernigotto, et al. (2013), Singh et al. (2015), Gong et al. (2012), Persson et al. (2006), Eskin and Türkmen (2008), Gasparella et al. (2011), Jaber and Ajib (2011b), Tavares and Martins (2007), Poirazis et al. (2008), Liang et al. (2015)	Atzeri, Pernigotto, et al. (2013), Fasi and Budaiwi (2015), Singh et al. (2015), Zemella et al. (2011), Yıldız and Arsan (2011), Gong et al. (2012), Ochoa and Capeluto (2008), Tsikaloudaki et al. (2012), Hammad and Abu-Hijleh (2010), Cheung et al. (2005), Chua and Kiang (2010), Florides et al. (2002), Capeluto (2003), Persson et al. (2006), Eskin and Türkmen (2008), Gasparella et al. (2011), Jaber and Ajib (2011b), Tavares and Martins (2007), Poirazis et al. (2008), Liang et al. (2015)	Atzeri, Pernigotto, et al. (2013), Fasi and Budaiwi (2015), Singh et al. (2015), Suga et al. (2010), Zemella et al. (2011), Capeluto (2003), Poirazis et al. (2008), Liang et al. (2015)	Kim et al. (2014), *Lee and Tavil (2007), Papaefthimiou, Syrrakou, and Yianoulis (2006), Contreras, Moyano, and Rico (2016), Znouda et al. (2007), Fasi and Budaiwi (2015), Singh et al. (2015), *Mainini et al. (2015), Hassouneh et al. (2010), Tuhus-Dubrow and Krarti (2010), Aldawood (2013), Laouadi et al. (2002), **Ihm and Krarti (2012), **Asadi, Gameiro, Antunes, and Dias (2012), Al-Homoud (2005), Al-Homoud (2009)	Singh et al. (2015), Suga et al. (2010), Tavares and Martins (2007), Poirazis et al. (2008)	Znouda et al. (2007), Mainini et al. (2015), Suga et al. (2010), Tuhus-Dubrow and Krarti (2010), Wang, Rivard, et al. (2005), Wang et al. (2006), Wang, Zmeureanu, et al. (2005), Bichiou and Krarti (2011), Ouarghi and Krarti (2006), Hasan, Vuolle, and Sirén (2008), Chua and Kiang (2010), Florides et al. (2002), Bambrook, Sproul, and Jacob (2011), Verbeeck and Hens (2005), **Ihm and Krarti (2012), **Asadi et al. (2012)	Papaefthimiou et al. (2006), Znouda et al. (2007), Mainini et al. (2015), Tuhus-Dubrow and Krarti (2010), Wang, Rivard, et al. (2005), Wang et al. (2006), Wang, Zmeureanu, et al. (2005), Bichiou and Krarti (2011), Hasan et al. (2008), Chua and Kiang (2010), Griego et al. (2012), Florides et al. (2002), Bambrook et al. (2011), Ouarghi and Krarti (2006), Verbeeck and Hens (2005), **Ihm and Krarti (2012)	Znouda et al. (2007), Mainini et al. (2015), Chua and Kiang (2010), Verbeeck and Hens (2005)
External venetian	Number of louvers	González and Fiorito (2015)	González and Fiorito (2015)	González and Fiorito (2015)	González and Fiorito (2015)				
	Width of louver	González and Fiorito (2015), Datta (2001)	González and Fiorito (2015), Datta (2001)	González and Fiorito (2015)	González and Fiorito (2015), Datta (2001)				
	Slope angle of louver	González and Fiorito (2015), Datta (2001), Palmero-Marrero and Oliveira (2010)	González and Fiorito (2015), Hammad and Abu-Hijleh (2010), Datta (2001), Palmero-Marrero and Oliveira (2010)	González and Fiorito (2015), De Carli and De Valeria (2009)	González and Fiorito (2015), Datta (2001)				
	Material properties	Atzeri, Pernigotto, et al. (2013)	Atzeri, Pernigotto, et al. (2013)	Atzeri, Pernigotto, et al. (2013)					
External overhang	Installation height of panel				*Manzan and Padovan (2015)		Wang et al. (2006)	Wang et al. (2006)	
	Width of panel	Wetter and Wright (2003), Gong et al. (2012)	Wetter and Wright (2003), Zemella et al. (2011), Gong et al. (2012), Florides et al. (2002)	Wetter and Wright (2003), Zemella et al. (2011), De Carli and De Valeria (2009)	*Manzan and Padovan (2015)		Wang, Rivard, et al. (2005), Wang et al. (2006), Bichiou and Krarti (2011), Florides et al. (2002)	Wang, Rivard, et al. (2005), Wang et al. (2006), Bichiou and Krarti (2011), Florides et al. (2002)	
	Slope angle of panel		Chua and Kiang (2010)		*Manzan and Padovan (2015)		Chua and Kiang (2010)	Chua and Kiang (2010)	Chua and Kiang (2010)
	Panel's distance from a window				*Manzan and Padovan (2015)				
	Panel's length		Cheung et al. (2005)						
Interior overhang	Width of panel			De Carli and De Valeria (2009)					
External vertical fins	Width of fins		Zemella et al. (2011)	Zemella et al. (2011)					
	Inclination of fins		Zemella et al. (2011)	Zemella et al. (2011)					
External roller	Material properties	Atzeri, Cappelletti, et al. (2013)	Atzeri, Cappelletti, et al. (2013)	Atzeri, Cappelletti, et al. (2013)					

Internal venetian	Slope angle of louver	Chan and Tzempelikos (2015), Oh et al. (2013)	Chan and Tzempelikos (2015), Oh et al. (2013)	Chan and Tzempelikos (2015), Oh et al. (2013), Ahmad et al. (2015)		Ahmad et al. (2015)
	Material properties	Chan and Tzempelikos (2015)	Chan and Tzempelikos (2015)	Chan and Tzempelikos (2015)		
Internal roller	Material properties	Chan and Tzempelikos (2015), Singh et al. (2015), Eskin and Türkmen (2008)	Chan and Tzempelikos (2015), Singh et al. (2015)	Yoon et al. (2014), Chan and Tzempelikos (2015), Singh et al. (2015)	Singh et al. (2015)	

*Primary energy demand.
**Total energy saving.

Optimization phase

The optimization phase comprises two main steps:(i) selecting a suitable optimization algorithm, available in the modeFRONTIER platform, and (ii) formulating an optimization problem with respect to visual comfort, thermal comfort, energy consumption and LCC.

Selection of an optimization algorithm

Multiple optimization algorithms have been developed and introduced for analysing big-data and resolving an optimization problem. Providing a rule for the selection of an optimization algorithm is generally infeasible due to the diversity and complexity of optimization problems (Nguyen et al., 2014). Among the investigated studies, 43 of them employed an algorithm to optimize window and blind design variables. Figure 4 shows the utilization of various optimization algorithms in the investigated studies. As seen in Figure 4 genetic algorithms were frequently used in optimizing window and blind design variables with respect to visual comfort, thermal comfort, energy consumption and LCC.

A possible explanation for the large utilization of genetic algorithms, including genetic algorithm (GA), the non-dominated sorting genetic algorithm (NSGA) and the non-dominated sorting genetic algorithm- II (NSGA-II), is their effectiveness in resolving optimization problems with several objectives (multi-objective optimization problems) (Nguyen et al., 2014). Manzan and Padovan (2015) and Deb, Pratap, Agarwal, and Meyarivan (2002) discussed the fact that NSGA-II is an efficient algorithm, because it has low computational complexity. In this paper, NSGA-II is selected for running an optimization in modeFRONTIER. The optimization process, using NSGA-II, starts by specifying window and blind design variables and codifying them. Codifications refer to the determination of upper and lower boundaries of the design variables. The upper and lower boundaries describe the highest and lowest values respectively that are assigned to a variable. Later, an initial population of $\boldsymbol{P}_0$ is generated. Furthermore, a random population of $\boldsymbol{P}_t$ will be generated from the earlier generation. Afterwards, an offspring population of $\boldsymbol{Q}_t$ will be produced from $\boldsymbol{P}_t$ through a combination of mutation and crossover processes. Mutation performs random changes in a solution in $\boldsymbol{P}_t$ and generates a new solution for $\boldsymbol{Q}_t$, while crossover combines two solutions in $\boldsymbol{P}_t$ and generates a new solution for $\boldsymbol{Q}_t$. At each generation, $\boldsymbol{P}_t$ and $\boldsymbol{Q}_t$ are combined and sorted based on the non-domination concept. N solutions are then selected for generating the next population $\boldsymbol{P}_{t+1}$. This process

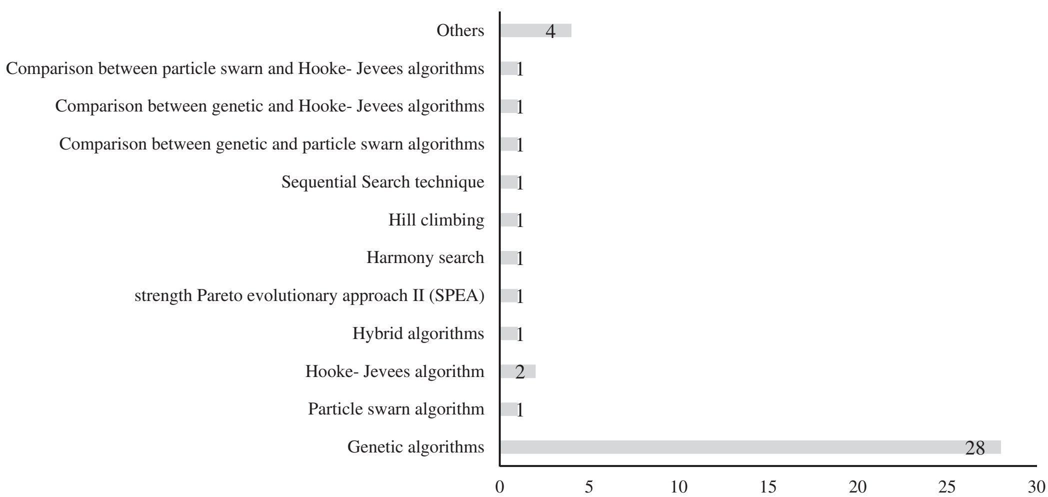

Figure 4. The utilization of different algorithms in optimizing window and blind design variables, with respect to visual comfort, thermal comfort, energy consumption and LCC.

continues until the maximum number of populations is achieved. When NSGA-II is terminated, optimization results are presented.

Formulation of the optimization problem

The mathematical formula of an optimization problem, with several objectives follows Equation (1) (Koziel & Yang, 2011):

$$\begin{array}{l} \text{minimize } \ F_1(\mathrm{x}) := [\mathrm{f}_1(\mathrm{x}),\ \mathrm{f}_2(\mathrm{x}), \ldots,\ \mathrm{f}_k(\mathrm{x})] \\ \qquad\qquad \text{and/or} \\ \text{maximize } \ F_2(\mathrm{x}) := [\mathrm{f}'_1(\mathrm{x}),\ \mathrm{f}'_2(\mathrm{x}), \ldots,\ \mathrm{f}'_k(\mathrm{x})] \\ \text{Subject to:} \\ \qquad \mathrm{g_i(x)} \leq 0 \quad \mathrm{i} = 1, 2, \ldots, \mathrm{m} \\ \qquad \mathrm{h_i(x)} \leq 0 \quad \mathrm{i} = 1, 2, \ldots, \mathrm{p} \end{array}, \tag{1}$$

where $\mathrm{x} = [x_1,\ x_2,\ \ldots,\ x_n]^T$ is the vector of design variables; f_i:$\mathrm{R}^n \rightarrow \mathrm{R}$ with $\mathrm{i} = 1,2,\ldots,\mathrm{k}$ are the objective functions; f'_i:$\mathrm{R}^n \rightarrow \mathrm{R}$ with $\mathrm{i} = 1,2,\ldots,\mathrm{k}$ are the objective functions; g_i and h_j with $\mathrm{i} = 1,2,\ldots,\mathrm{m}$ and $j = 1,2,\ldots,\mathrm{p}$ are the constraints functions.

As seen in Equation (1), optimization objectives and constraint functions are needed for developing an optimization problem. In the context of window and blind design, objective functions are the metrics used for assessing different criteria of visual comfort, thermal comfort, energy consumption and LCC (Carlucci et al., 2015b). Considering visual comfort, amount of daylight, glare and daylight uniformity are found to be the main evaluated criteria (Table 1). Earlier studies introduced multiple metrics to evaluate the visual comfort criteria (Carlucci, Causone, De Rosa, & Pagliano, 2015a). In this paper, since EnergyPlus was selected as a simulation tool, only metric which can be calculated by EnergyPlus, are selected. EnergyPlus (version 8.8.0) can evaluate the amount of daylight by calculating the number of hours, when daylight illuminance at a reference point exceeded a predefined threshold (EnergyPlus, 2018). With respect to glare, EnergyPlus (version 8.8.0) calculates the number of hours, when daylight glare index at a reference point exceeded a predefined threshold. The daylight glare index evaluation comprises four main glare levels, including 'just imperceptible', 'just acceptable', 'just uncomfortable' and 'just intolerable' (Lee & Tavil, 2007). The abovementioned levels correspond to daylight glare index of 10, 16, 22 and 28, respectively (Lee & Tavil, 2007).

Daylight uniformity is a metric, which shows the distribution of daylight illuminance within a given area. But, one of the main limitations with EnergyPlus (version 8.8.0) is the feasibility of calculating daylight uniformity. To overcome the abovementioned limitation, Ochoa et al. (2012) presented an approach; they first specified two lighting zones in a single office using EnergyPlus, later they obtained the daylight illuminance at two reference points (P1 and P2), which were positioned at the centre of each lighting zone at 0.8 m from floor level. P1 reference point was closer to the window, while P2 reference point was closer to the back of the room. The reference points had a viewpoint looking directly to the window. Later, the daylight uniformity (U) was calculated following Equation (2) and set to be equal or smaller than 3.5 for a minimum 50% of the occupancy time.

$$\mathrm{U} = \frac{\text{average yearly illuminance at P1}}{\text{verage yearly illuminance at P2}}. \tag{2}$$

In another attempt, Loura, De Assis, and de Souza (2009) calculated daylight diversity in an office, using EnergyPlus. Diversity studies the distribution of daylight illuminance within a boundary 0.5 m from the walls (Sayigh, 2015). The daylight diversity is calculated as the ratio of the maximum daylight illuminance to the minimum illuminance, that should not exceed 5:1 (Ochoa et al., 2012). To calculate diversity, Loura et al. (2009) used EnergyPlus to generate four illuminance maps on 6th, 7th, 14th and 15th of August at 12:00 o'clock. Later, the diversity was calculated for each day. However, Bülow-Hübe (2007) discussed that illuminance maps for calculating daylight diversity should be obtained at least on 21th of March, 21th of June and 21th of December at 12 o'clock, which represent the midpoint, largest and smallest illuminance over a year.

In this paper, the approach by Ochoa et al. (2012) is selected for evaluating the daylight uniformity. This decision was made, due to the simplicity of the abovementioned approach in quantifying the daylight uniformity, using EnergyPlus. Furthermore, the presented approach by Ochoa et al. (2012) evaluates the daylight distribution over a year and provides a single value for daylight uniformity. But, using the illuminance map for calculating diversity provides at least three distinct values for diversity.

Considering thermal comfort, EnergyPlus calculates air temperature, mean radiant temperature, operative temperature and Fanger thermal comfort metrics, including predicted mean mote (PMV) and predicted percentage of dissatisfied (PPD). The PMV describes thermal sensation using a seven-point scale as follows: +3 hot, +2 warm, +1 slightly warm, 0 neutral, −1 slightly cool, −2 cool, −3 cold (Khamporn & Chaiyapinunt, 2014; Pourshaghaghy & Omidvari, 2012). According to Pourshaghaghy and Omidvari (2012), PMV is a suitable metric for evaluating thermal comfort. Because, in calculating PMV, metabolic rate, clothing insulation, ambient air temperature, radiant temperature, air velocity and relative humidity are all considered. The PMV within the −0.5 to + 0.5 range represents a comfortable thermal environment. The corresponding PPD is less than or equal to 10%, while the PMV is within the −0.5 to + 0.5 range (Pourshaghaghy & Omidvari, 2012). A lower PPD represents an environment with lower thermal discomfort. In this paper, PMV is selected to evaluate the performance of different window and blind designs with respect to thermal comfort.

The investigated studies analysed the energy performance of different window and blind designs by calculating total energy consumption, the energy needed for space heating, cooling also electricity needed for lighting and artificial ventilation. EnergyPlus (version 8.8.0) is capable of calculating multiple metrics to evaluate the energy performance of different window and blind designs. In this paper, total energy consumption is selected for evaluating the energy performance of different window and blind designs. Total energy consumption is calculated based on the sum of energy demand for space heating, cooling, also electricity demand for lighting and artificial ventilation

With respect to LCC, EnergyPlus (version 8.8.0) can calculate present value by considering investment cost, consumption cost, energy price escalation and use adjustments, based on changes to the actual energy consumption in future (EnergyPlus, 2018). The energy price escalation in EnergyPlus is specified using NIST 135 handbook (EnergyPlus, 2018). However, NIST 135 presents the energy price escalation only for the United State (EnergyPlus, 2018), which can cause for concern regarding the accuracy of calculated present value for other countries. According to Sundqvist and Allansson (2006), the present value can also be calculated using Equation (3) and (4);

$$K_n = \sum_{t=0}^{n} (D_t + U_t) * \frac{1}{(1+r)^t} + I_0. \tag{3}$$

$$D_t = E * \alpha (1+\beta)^t. \tag{4}$$

Where K_n is present value during lifespan of n year; U_t is annual maintenance cost; D_t is annual energy consumption cost; r: interest rate; t: lifespan of n years; E is annual energy consumption (kWh/m^2); α is energy price per kwh/m^2; β is inflation in energy price (%); I_0 is the investment cost

If the energy price for heating, cooling and electricity varies from one to another, then the $\boldsymbol{D_t}$ should be calculated based on sum of the annual energy price for heating, cooling and electricity and in conjunction with their respective inflation rate (Sundqvist & Allansson, 2006). EnergyPlus (version 8.8.0) allows calculating present value using Equations (3) and (4).

Once metrics for assessing different criteria of visual comfort, thermal comfort, energy consumption and LCC are specified, an optimization problem should be developed. In this paper, the optimization objectives comprise the number of hours when daylight illuminance at a reference point exceeded a predefined threshold, the number of hours when daylight glare index at a reference point exceeded a predefined threshold, total energy consumption and present value. Furthermore, two constraint functions, including daylight uniformity equal or smaller than 3.5 and PMV within the –0.5 to +0.5 range are considered. The constraint functions ensure the fulfilment of daylight uniformity and PMV requirements. The mathematical formulation of the optimization problem can be shown as Equation (5);

$$\begin{array}{c} \text{minimize } \; F_1(\mathrm{x}) := [H_{\mathrm{DGI}>Z'}, E_{\mathrm{total}}, K_n] \\ \text{and} \\ \text{maximize } \; F_2(\mathrm{x}) := [H_{illu>Z}] \\ \text{Subject to:} \\ U \leq 3.5 \\ -0.5 \leq PMV \leq 0.5 \end{array} \quad . \tag{5}$$

Where $H_{DGI>Z'}$ represents the number of hours, when daylight glare index at reference point exceeded predefined threshold (Z'); E_{total} refers to the total energy needed for space heating, cooling and electricity needed for lighting and artificial ventilation; K_n represents the present value of different window and blind designs; $H_{illu>Z}$ refers to the number of hours, when daylight illuminance at reference point exceeded predefined threshold (Z); $U \leq 3.5$ represents a daylight uniformity equal or smaller than 3.5 and; $-0.5 \leq$ PMV ≤ 0.5 refers to PMV within the –0.5 to + 0.5 range.

Post-processing phase

Post-processing phase refers to the selection of a suitable MCDM method. There are numerous MCDM methods that can be used for ranking optimization results. Mardani et al. (2017), Jato-Espino, Castillo-Lopez, Rodriguez-Hernandez, and Canteras-Jordana (2014) and Wang, Jing, Zhang, and Zhao (2009) analysed the utilization of different MCDM methods within the energy management, construction and sustainability fields. The presented results by abovementioned studies show that Analytical Hierarchy Process (AHP) was mostly used by earlier studies. Furthermore, AHP has been used for selecting a trade-off solution in the field of indoor environment quality (Lai & Yik, 2009), passive design (Chong & Shyang, 2014), sustainability (Alwaer & Clements-Croome, 2010; Bhatt, Macwan, Bhatt, & Patel, 2010; Chandratilake & Dias, 2013; Markelj, Kitek Kuzman, Grošelj, & Zbašnik-Senegačnik, 2014; Wong & Li, 2008) and daylight performance (Arpacioglu & Ersoy, 2013).

According to Podgórski (2015), the AHP method is implemented as follows:

(1) Breaking the MCDM problem down into several levels, including the goal, AHP objectives and their respective criteria. This process creates a hierarchy model (Figure 5).
(2) Performing pairwise comparisons among the objectives of the AHP and among their respective criteria. The pairwise comparisons should be conducted as indicated by the numerical ratings presented in Table 4.

This process generates a comparison matrix. Matrix A shows the comparison matrix developed between criteria.

$$A = \begin{array}{c} \\ \text{Criteria 1} \\ \text{Criteria 2} \\ \ldots \\ \text{Criteria n} \end{array} \begin{array}{c} \begin{array}{cccc} \text{Criteria 1} & \text{Criteria 2} & \ldots & \text{Criteria n} \end{array} \\ \begin{bmatrix} 1 & a_{1,2} & \ldots & a_{1,\mathrm{n}} \\ 1/a_{1,2} & 1 & \ldots & a_{2,\mathrm{n}} \\ \ldots & \ldots & 1 & \ldots \\ 1/a_{1,\mathrm{n}} & a_{\mathrm{n},2} & \ldots & 1 \end{bmatrix} \end{array} .$$

Where $\boldsymbol{a_{i,j}}$ indicates that criteria i are compared to criteria j. On the diagonal of the matrix, $\boldsymbol{a_{i,j}}$ is equal to 1 since i = j. When the comparison matrix is developed, the weight of each criterion should be calculated as follows:

- Calculating the sum of each column in the matrix ($\sum \boldsymbol{a_j}$).

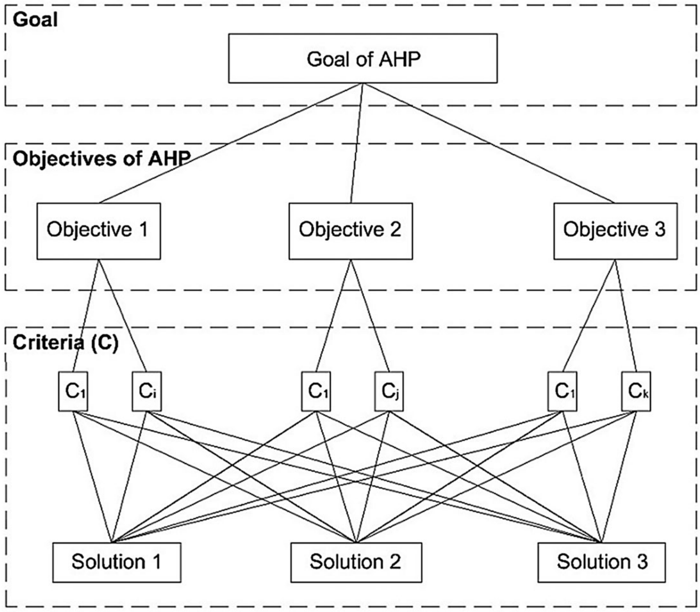

Figure 5. Illustration of AHP hierarchy model.

- Dividing each $\boldsymbol{a_{i,j}}$ in column j by the $\sum \boldsymbol{a_j}$ calculated in the previous step (normalization of the matrix).
- Obtaining the average of each row in the normalised matrix ($\overline{\boldsymbol{a}_i'}$). $\boldsymbol{a}_i'$ represents the weight of a criterion in row i.

(3) Evaluating the performance of optimization results with respect to each criterion and obtaining the weight vector for the solutions using modeFRONTIER. The modeFRONTIER compares the solutions in relation to each criterion (Matrix B). The weight calculation process is similar to step 2.

$$B = \begin{array}{c} \\ \text{Solution 1} \\ \text{Solution 2} \\ \dots \\ \text{Solution n} \end{array} \begin{array}{c} \begin{array}{cccc} \text{Solution 1} & \text{Solution 2} & \dots & \text{Solution n} \end{array} \\ \begin{bmatrix} 1 & a_{1,2} & \dots & a_{1,n} \\ 1/a_{1,2} & 1 & \dots & a_{2,n} \\ \dots & \dots & 1 & \dots \\ 1/a_{1,n} & a_{n,2} & \dots & 1 \end{bmatrix} \end{array}.$$

(4) Determining the global weight vector for each solution and ranking them to select a trade-off solution using modeFRONTIER. The solution with highest global weight is known as the trade-off solution. The global weight is the sum of the products of the weight of a given solution and the

Table 4. Pairwise numerical rating (Saaty, 2008).

AHP, relative importance		Numeric rating
Equal importance	Two factors contribute equally to the objective	1
Somewhat more important	Experience and judgment slightly favour one over the other	3
Much more important	Experience and judgment strongly favour one over the other	5
Very much more important	Experience and judgment very strongly favour one over the other. Its importance is demonstrated in practice	7
Absolutely more important	The evidence favouring one over the other is of the highest possible validity	9
Intermediate values	When compromise is needed	2,4,6,8

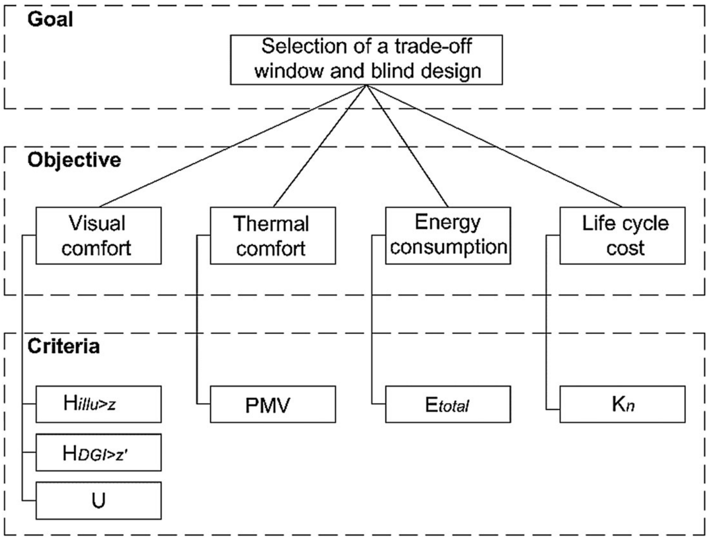

Figure 6. Hierarchy model for selecting windows and blinds.

weights of the criteria. For instance, if $\boldsymbol{W_{s,1}}$ is the weight of the first solution and $\boldsymbol{W_{c,i}}$ is the weight of the criteria i, the global weight of the first solution is as shown in Equation 6:

$$\text{Global weight of solution 1 } (GW_1) = \sum_{i=1}^{i=n} W_{s,1} \times W_{c,i}. \quad (6)$$

Using the AHP to select a trade-off window and blind design creates a hierarchy model as illustrated in Figure 6.

To perform pairwise comparisons, one should determine the *relative* importance among visual comfort, thermal comfort, energy consumption, LCC and among their respective criteria. Hence, the consistency of the pairwise comparisons should be tested. For this reason, consistency ratio (CR) can be quantified for each matrix following equation 7;

$$\frac{CR = \lambda_{max} - n}{(n-1) \times RI.} \quad (7)$$

Where λ_{max} is the maximum eigenvalue of the developed matrices in step 2; n is the number of elements in the developed matrices;

RI or the random consistency index in Equation (7) is a reciprocal matrix (Hotman, 2005). The average RI of sample size $n = 10$ is shown in Table 5.

Decision-making framework

The decision-making framework was developed by integrating NSGA-II as an optimization algorithm and AHP as a MCDM method (Figure 7). The integration is automated using EnergyPlus and modeFRONTIER. When using a decision-making framework users should follow three main steps. Step one,

Table 5. Random consistency index (RI).

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

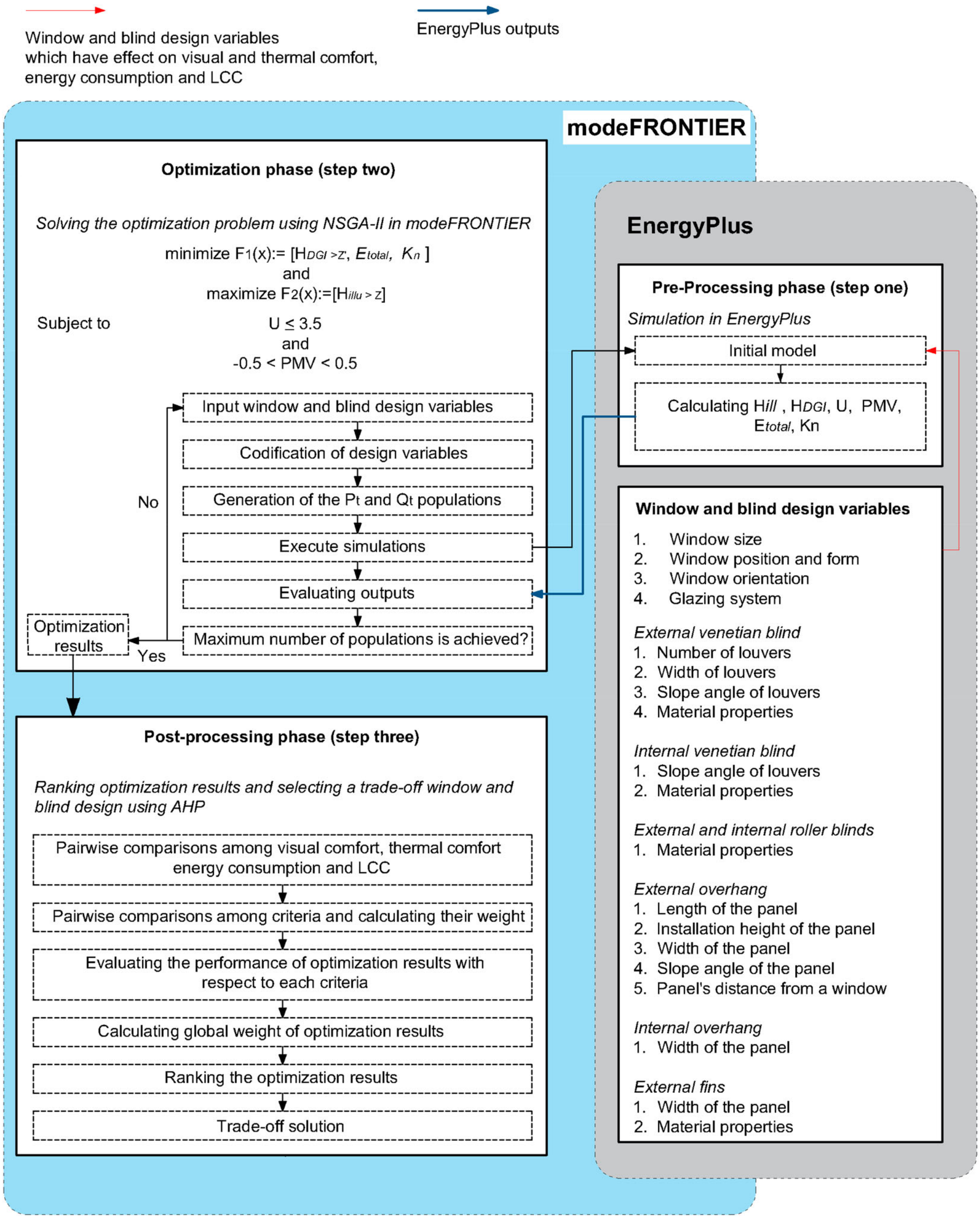

Figure 7. The decision-making framework.

which includes results obtained in pre-processing phase, starts by developing an initial model of a building or a room in EnergyPlus and providing data regarding the model's location, geometry, occupancy schedule, control system and heating, cooling and ventilation systems. In addition, material specifications of envelopes including walls, floor, ceiling, windows and blinds are needed to execute simulations in EnergyPlus. Detailed information is also needed for calculating the main criteria determined in the pre-processing phase, including H_{illu}, H_{DGI}, U, PMV, E_{total} and K_n. To calculate K_n, information should be provided regarding the investment cost of windows and blinds, maintenance cost during the lifespan, energy price per kWh/m², interest rate and energy price inflation. Furthermore, 19 window and blind design variables, which were determined in the pre-processing phase, are presented in step one. The design variables have an impact on visual comfort, thermal comfort, energy consumption and LCC.

Step two comprises results obtained in the optimization phase and begins by running an optimization using NSGA-II algorithm. For this purpose, the window and blind design variables presented in step one should be specified in modeFRONTIER. According to Nguyen et al. (2014), 15 design variables on average were previously studied when performing optimization. However, no clear formula has been found, which restricts the number of variables in performing optimization. Later, window and blind design variables should be codified and $\boldsymbol{P_t}$ and $\boldsymbol{Q_t}$ populations should be generated. When using NSGA-II, it is difficult to define features such as population size, number of generations, mutation and crossover probabilities as these are dependent on the optimization problem and its complexity. To have suitable settings in NSGA-II, Carlucci et al. (2015b) analysed 68 studies and investigated the variation in the population size, number of generations, mutation and crossover probabilities. The analysed studies used a genetic algorithm and resolved an optimization problem in the context of building envelopes and systems. Results presented by Carlucci et al. (2015b) indicated that the maximum population size and number of generations were about 1000 and 2000 respectively. The crossover probability varied between 0.5 and 1, while the mutation probability switched between 0 and 0.4. When all features are set, the NSGA-II algorithm changes the value of design variables to generate new population of the window and blind designs and iterates the simulation process. The optimization process is terminated, when the maximum number of populations is achieved.

Step three includes results obtained in the post-processing phase and starts by employing AHP in modeFRONTIER. For this purpose, pairwise comparisons should be performed among visual comfort, thermal comfort, energy consumption, LCC and among their respective criteria. The pairwise comparisons are conducted using numerical ratings presented in Table 4. Later, CR should be calculated to ensure the consistency of pairwise comparisons. However, modeFRONTIER (version 5.0.0) is uncapable of calculating CR, therefore equation 7 should be used to test the consistency of comparison matrices. Finally, modeFRONTIER calculates the weight of each criterion, evaluates the performance of optimization results with respect to each criterion and determines the global weight of the optimization results. Design with the largest global weight is presented as a trade-off design. Figure 7 shows the different steps required in using the decision-making framework.

Conclusion

The decision-making framework can be used by architects and designers in selecting a trade-off window and blind design during the both design and renovation phases. Opportunities in analysing various window and blind design variables in the design phase may be larger than the renovation phase. For example, changing orientation may not be feasible in the renovation phase. Furthermore, the decision-making framework can be used in selecting a trade-off windows and blinds for both residential and commercial buildings. But, there are various types of spaces in buildings and each space has its own functionality and characteristics. Hence, in using the decision-making framework, distinct comparison matrices should be developed for spaces with different functionalities.

The decision-making framework was developed to select a trade-off window and blind design through intelligent use of simulation in analysing big-data in the built environment, energy and cost sectors. Application of the framework helps to fulfil the requirements of the EU Energy Performance of Buildings Directive about minimising energy consumption and ensuring minimum visual and thermal thresholds. But the decision-making framework differs from the frameworks developed in earlier research. This decision-making framework concentrates solely on the window and blind design and establishes an integration between NSGA-II and AHP to resolve the conflicts. Other integrations, including the integration of genetic algorithm (GA) with AHP (Yousefi, Ghodusinejad, & Noorollahi, 2017) and NSGA-II with evidential reasoning as an MCDM method (Monghasemi et al., 2015), were employed for analysing multiple designs and resolving diverse conflicts.

The goal for future research is to apply the decision-making framework, for example via a case study and thereby evaluate the strength of the framework in managing conflicts between visual comfort, thermal comfort, energy consumption and LCC and selecting a trade-off design.

Notes

1. EnergyPlus (EnergyPlus, 2018), IDA ICE (IDAICE, 2016), Diva for Rhino (Diva4Rhino, 2016), Grasshopper (Mangkuto et al., 2016) and COMFEN (Lawrence Berkeley National Laboratory, 2016)
2. modeFRONTIER has various of nodes including logic nodes, data nodes, file nodes, application nodes, script nodes, CAD nodes, CAE nodes and networking nodes. Nodes are executable components which have data and accomplish some transformations over the data, later forward the data to the next node (Sousa, 2012). DOS-Batch and EasyDriver nodes are two available script nodes.

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