Mathematical optimisation of location and design of windows by considering energy performance, lighting and privacy of buildings

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Abstract

Purpose – The Middle East and North Africa (MENA) region is known for its extreme weather conditions during Summer. A major determinant of the sustainability of the design of a building is its fenestrations. The purpose of this paper is to explore the problem of designing and locating windows on building facades such that a number of relevant criteria to the MENA region are optimised, including solar heat gain, privacy, daylighting and cost of installation.

Design/methodology/approach – A multi-objective optimisation problem is proposed with the focus on capturing the requirements of residential dwellings in the MENA region. Since the problem contains conflicting objectives that need to be optimised, a lexicographic approach is adopted. In order to display the Pareto curve, a bi-objective analysis based on the ε-constraint method is utilised.

Findings – The conflicting nature of the proposed problem is indicated via the Pareto optimal solutions yielded. Depending on the preference of criteria adopted in lexicographic optimisation, the location of the windows on the building façade tends to change. The bi-objective analysis indicates the importance of balancing out the daylight factor against each of privacy, solar heat gain and installation cost criteria. Furthermore, an analysis conducted in three major cities in the MENA region highlights the discrepancy in design alternatives generated depending on the local climatic condition.

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Originality/value – This work proposes a novel mathematical optimisation model which focuses on producing a sustainable design and layout for windows on the facades of residential dwellings located in the MENA region. The proposed model provides designers with guidance through an automated support tool that yields optimised window designs and layout to ensure the sustainability of their designed buildings.

Keywords Multi-objective, Mathematical optimization, Mixed integer programming, Pareto curve, Window design, Window location

Paper type Research paper

1. Introduction

Available literature indicates that buildings are responsible for 20–40 per cent of the total energy consumption in different countries (Pérez-Lombard *et al.*, 2008). With this mind, investigating different strategies to reduce this significant energy consumption has been the target of worldwide research over the past several decades (Akbarnezhad and Xiao, 2017; Intergovernmental Panel on Climate Change, 2007). Among various factors affecting the energy performance of buildings, the design decisions made in early phases have been shown to play a critical role (Bogenstätter, 2000; Hammad *et al.*, 2018). Therefore, energy performance is highlighted as one of the essential criteria to be considered in making the initial design decisions (Acosta *et al.*, 2016).

Accounting for energy performance in the design of buildings is imperative especially in regions with more extreme climates including the Middle East and North Africa (MENA) region (Rana *et al.*, 2017). The MENA region is particularly renowned for its climatic extremes during Summers, where temperatures can rise to more than 45°C (Lelieveld *et al.*, 2016). Given the hot climate, energy use for cooling purposes accounts for the highest share of energy in buildings of the MENA region (Arouri *et al.*, 2012). It is reported that energy use by the built environment will grow by 34 per cent in the next 20 years (Pérez-Lombard *et al.*, 2008). Additionally, buildings in some MENA countries are responsible for around 42 per cent of the total energy use within the region (Alnaser *et al.*, 2008). These figures are comparatively higher when contrasted with the statistics from the USA and Canada, where building energy use accounts for nearly 28–30 per cent of total energy use, respectively (US Department of Energy, 2003; Natural Resources Canada, 2013). One of the early design decisions made for a building is the placement and sizing of windows. Windows influence the building's thermal and daylight characteristics, due to heat gain and loss, and daytime illumination that ensues (Das and Paul, 2015; Li, 2010). Window design is therefore a critical factor in determining the effectiveness of passive solar designs of buildings (Jaber and Ajib, 2011a). In particular, window glazing has been reported to highly impact the total energy use of residential buildings (Freire *et al.*, 2011; Ihm *et al.*, 2012). In the USA, windows are responsible for 24 and 32 per cent additional loading on heating, ventilation and air conditioning (HVAC) systems installed in residential and commercial buildings, respectively (Arasteh DK *et al.*, 2006).

Alibaba (2016) investigated extensively, through simulation models, the optimum window to external wall ratio for offices in hot climates. Yoo *et al.* (2005) reported that around 30 per cent of total changes in the energy requirements of residential buildings are attributed to heat transfers through windows. The cooling load that is associated with the energy consumption of residential buildings is largely influenced by the heat gain and solar radiation incident onto the windows (Berger *et al.*, 2014; Ke *et al.*, 2013). The energy gain due to solar radiation onto windows in buildings depends on the thermal properties of the window glazing (Fasi and Budaiwi, 2015). The daylight that comes through windows can also reduce the lighting requirements of the building, as it is considered to be a passive measure for reducing the building's energy consumption rates (Ke *et al.*, 2013; Lim *et al.*, 2012; Shen and Tzempelikos, 2013). Savings in artificial energy needs for lighting and the corresponding CO_2 emission mitigation, due to passive daylight measures, were evaluated by Chel *et al.* (2009) to be at 973 kW h/year and 1,526 kg/year, respectively. A clear conflict in heat gain and lighting requirements leads designers to compromise when developing suitable designs.

Identifying the optimal location and size of the windows finds particular importance in the MENA region where heat transfer from windows is a major challenge (Askar *et al.*, 2001). Decisions of window design and placement can be utilised as a measure to mitigate the impacts of soaring temperatures during Summer; additionally, emphasis on privacy inside dwellings from the outer world is well too common in the MENA region. Jaber and Ajib (2011b) concluded that the optimum choice of window size contributes to a 26 per cent of annual energy consumption savings, if other building design measures, such as material composition of exterior envelope, are kept constant. Hassouneh *et al.* (2010) mentioned that massive energy savings are possible depending on the design decision for window glazing and size.

However, despite its emphasised importance, little effort has been made in the literature to develop methods and tools that aid designers in optimising the size and location of the windows by considering energy, privacy and aesthetic requirements.

In this paper, and based on the gap identified in the literature, we propose a window location problem (WLP) for optimising the location and size of windows in residential buildings, with particular emphasis on buildings located in the MENA region. The proposed model is founded on location theory which has been thoroughly investigated in the field of operational research (Hale and Moberg, 2003) and used to address several other common problems faced by the construction industry including the facility layout problem (Drira *et al.*, 2007; Hammad *et al.*, 2016a) and the facility location problem (Drezner and Hamacher, 2004; Hammad *et al.*, 2016b, 2017). The orientation of buildings and window sizing was studied by El Ansary and Shalaby (2014) and Wang *et al.* (2005), yet these studies did not emphasise the location of windows on the building façade. Skylight design has also been addressed through developing optimisation methods based on daylighting performance (Acosta *et al.*, 2013; Futrell *et al.*, 2015). However, to the best of our knowledge, there has not been many attempts at utilising location theory to optimise the location and size of the windows in a building.

Our proposed model accounts for the impacts of various objective functions through formulating them mathematically within a mixed integer non-linear programming (MINLP) model (Boukouvala *et al.*, 2016). The criteria considered include the solar heat gain, the privacy of the dwelling, the lighting requirement and the cost of installation of the windows. The conflicting nature of objectives is represented through solving a multi-objective optimisation problem.

The paper is divided as follows. In the next section, the problem description is presented and a mathematical model for the WLP is proposed. The model is later tested on a realistic case study and finally concluding remarks are offered.

2. Problem description

The problem investigated in this paper is one that considers the location and design of windows in residential dwellings within the MENA region, in order to optimise several conflicting objective functions. At the same time, a set of specific constraints are modelled to ensure the feasibility of the solution.

Whenever a decision maker is faced with multiple objectives, where each one needs to be optimised, the realisation of a solution that satisfies all defined criteria can be a daunting task. This is especially true if a large-scale project is worked on and it is desired to find the optimum location of windows that result in a sustainable building. For residential buildings in the MENA region, designers will be faced with a number of objective functions that happen to be conflicting. As a result, a multi-objective optimisation model (Hammad *et al.*, 2016a; Wang *et al.*, 2005) is proposed to deal with the issue of locating windows in residential dwellings, all the while satisfying a set of architecture constraints.

Figure 1 gives an overview of the framework adopted for optimising the location of residential windows. The first step requires the initialisation of the building form. This will be used as input into the simulation. It involves specifying the orientation of the building, the HVAC system that will be adopted, the number of occupants of the building, room

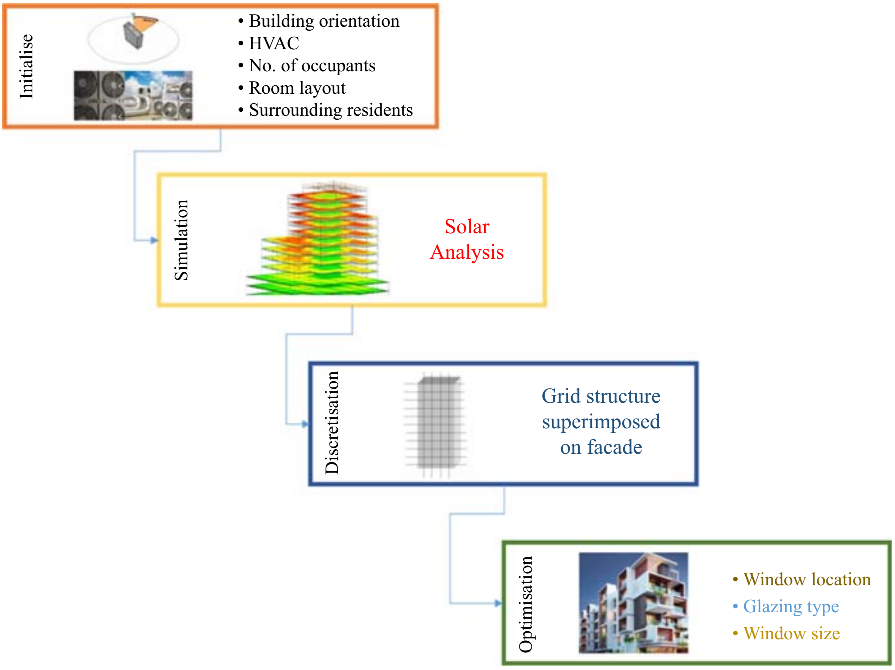


Figure 1.
Overview of proposed method

layout and the surrounding residents. The orientation of the building will act as a key indicator of the solar radiation that results on the building façade. The HVAC system and the number of occupants determine the internal temperature of the building, while the room layout is to specify where on a façade a window might be necessary (e.g. kitchen). Finally, the surrounding residents' locations are to enable the formulation and assessment of the privacy indicator to be included as a criterion that is optimised.

A solar analysis is then conducted to determine the total solar radiation incident upon the facade of the building under consideration. Each side of the building is discretised into a grid so that a discrete value for the radiation is associated with each grid. Finally, the optimisation model is run in order to determine the optimum location, size and glazing system to be adopted.

It is important to note that the number of windows to be installed is not given at the start of the optimisation, as it is left as a decision variable to be determined. An upper bound can be specified, however, for the maximum number of windows that can be installed. Let M denote the set of all discrete grid points on the façade of the building analysed (see Figure 1). The upper bound will then be given as $|M|$ which is the total number of discrete grid points.

In the next sections, the description of the objective functions and constraints making up the optimisation model are given. The set notation adopted in the model is given in Table I.

2.1 Objective functions

A total of four criteria are defined to satisfy the requirements of residential buildings in the MENA region. These are discussed next.

2.1.1 Heat gain from windows. The first of these objectives relates to the solar heat gain that ensues due to the hot climate and is formulated based on the heat that is gained from windows. Heat gain through windows can be assessed based on two main measures (Rubin, 1982). The first is the solar heat gain, which is a function of the solar heat gain coefficient of

Notation	Definition
Sets	
$m \in M$	Each grid point of the discretised facade
$i \in 1, ..., I$	Set of all windows where $I = \lvert M \rvert$
$g \in G$	Glazing system adopted
$r \in R$	Room in the building
$r \in RR \subset R$	Room that must have a window
$m \in M_r$	Set of discrete grid point associated with room r
$n \in N$	Set of neighbours around building under consideration
SR	Set of grids belonging to specified locations for requests made by clients to have a window positioned at a particular location
Parameters	
$\underline{SH}_m$	Solar radiation at each grid point
$\overline{A}$	Upper bound on the area of the window
$SHGC_g$	Solar heat gain coefficient associate with each glazing system adopted
UV_g	UV function of the glazing system
ΔT	Difference in temperature in Celsius between outer and inner space, dependent on the HVAC system adopted
$\underline{\varepsilon}$	Factor to account for external obstruction
$\overline{U}$	Utilisation factor for light
H_{in}	Predefined visibility matrix which equals 1 if window i is visible from neighbour n, and 0 otherwise
β_{mr}	Binary parameter which equals 1 if discrete grid point m is associated with room r
T_m	Width of gird point m
U_m	Length of gird m
t_m^x	x-coordinate centroid of grid point m
u_m^y	y-coordinate centroid of grid point m
FF	Large number equal to height plus width of the largest façade of the building (to ensure constraint satisfaction)
ϕ_n	Angle between line joining neighbouring dwelling and the considered building window, with respect to the normal
t_m^x	x-coordinate centroid of grid point m
u_m^y	y-coordinate centroid of grid point m
Variables	
A_i	Area of window i
A_{ir}	Total area of window i associated with room r
AW_r	Total area of windows associated with room r
DF_r	Daylight factor associated with room r
ϕ_i	Angle between window i and the normal to the window
V_i	Visibility of window i from all neighbouring points
$V_{i,n}$	Visibility of window i from neighbouring point n
$f(A_i)$	Function indicating the cost of installing window as a function of the area of the window i
L_i	Length of window i in the vertical y direction
W_i	Width of window i in the horizontal x-direction
x_i	x-coordinate centroid of window i
y_i	y-coordinate centroid of window i
z_{im}	Binary variable which equals 1 if window i is placed at grid point m, and 0 otherwise
γ_{gi}	Binary variable which equals 1 if glazing system g is adopted, and 0 otherwise
μ_{ij}^x, μ_{ij}^y	Auxiliary binary variables

Table I.
Set notation

the window and its area. The second measure is the gain through heat conduction, which is a function of the U-value of the window, the temperature difference between the outer and inner space and the area of the window. To minimise solar and conduction heat gain the following equation is formulated:

$$\min \ B_1 = \sum_{g \in G} \sum_{i} \sum_{m \in M} SH_m \cdot A_i \cdot SHGC_g + UV_g \cdot \Delta T \cdot A_i. \tag{1}$$

The area of the window, A_i, is defined based on the length and width of each window, both of which happen to be variables in our proposed model. The solar heat radiating from the sun onto the façade, SH_m, is obtained through a solar analysis simulation.

2.1.2 Daylight factors. The daylight factor is the most common metric adopted in architecture to assess the daylighting of a building (Chel *et al.*, 2010; Reinhart, 2004). It defines the ratio of the illuminance inside a room to that observed outside under overcast sky conditions (CIE, 2011). In this paper, we adopt the daylight factor formulation given by the Illuminating Engineering Society (Baker *et al.*, 2015). The following equation defines the average daylight factor measured across all rooms of the building analysed:

$$\max \ B_2 = \frac{\sum_r DF_r}{r}, \tag{2}$$

where:

$$DF_r = \frac{AW_r \varepsilon \overline{U}}{\sum_i A_{ir}} \quad \forall r \in R. \tag{3}$$

Equation (3) is defined to specify the daylight factor, DF_r, for each individual room.

A constraint that highlights the minimum daylight that is required in each room to satisfy building regulations in the region can be formulated as follows: $DF_r \geqslant \tau$, where τ is the threshold specified by the regulations for the daylight factor.

2.1.3 Privacy. To measure the privacy of the residential dwelling, an adaptation of the visibility formulations proposed by Orti *et al.* (1996) is utilised. As a result, to assess the visibility of all windows in the building considered, the following equation is formulated:

$$\min \ B_3 = \sum_{m \in M} \sum_{i \in 1,\ldots,|M|} V_i, \tag{4}$$

where:

$$V_i = \sum_{n \in N} \sum_{m \in M} V_{i,n} z_{im} \quad \forall i \in 1, \ldots, |M|, \tag{5}$$

$$V_{i,n} = \frac{\cos \ \phi_i \ \cos \ \phi_n}{2d} H_{in} \quad \forall i \in 1, \ldots, |M|, \forall n \in N \tag{6}$$

We point out that Equation (4) is minimised as we aim to decrease the visibility of the windows to surrounding neighbours and hence increase the privacy of the dwelling.

Equation (5) specifies the total visibility for all windows utilised, while Equation (6) specifies the visibility of the individual window on the building under consideration with respect to a window on a neighbouring dwelling n. The matrix H_{in} is predefined by the designer so that it equals 1 if window i is visible from neighbour n, and 0 otherwise. The concept behind Equation (6) is illustrated in Figure 2.

2.1.4 Installation cost. The installation cost of the windows is given in Equation (7). In this study, it is assumed that the cost of installing a window depends on two main measures, namely the glazing system chosen and the size of the window. This is reflected in Equations (8) and (9), respectively:

$$\min \ B_4 = \sum_{i \in 1,\ldots,|M|} CG_i + CS_i, \tag{7}$$

where:

$$CG_i = \sum \gamma_{gi} C_g \quad \forall i \in 1, \ldots, |M|, \tag{8}$$

$$CS_i = \sum_{m \in M} z_{im} f(A_i) \quad \forall i \in 1, \ldots, |M|. \tag{9}$$

As is noticed from Equation (9), the cost associated with the size of the window is made up of a function that is dependent on the area of the window A_i. In this study, linear form can be assumed for $f(A_i)$.

2.2 Constraints

The following constraints make up the feasible region of the WLP.

2.2.1 Area-related constraints. Equation (10) defines the area of the window as the length multiplied by its width, both of which are variables. Equation (11) specifies that A_i will have a value only when a window is located. Equation (12) specifies the total area of the windows that are located within a room:

$$A_i = L_i W_i \quad \forall i \tag{10}$$

$$A_i \leqslant z_{im} \overline{A} \quad \forall i \tag{11}$$

$$AW_r = \sum_{m \in M_r} \sum_{i \in F} L_i W_i z_{im} \quad \forall r \in R \tag{12}$$

2.2.2 Location-related constraints. Equation (13) specifies that each room in the building belonging to set *RR* (i.e. compulsory to have a window in) should have at least one window. Equation (14), on the other hand, specifies that a window can be located at a specific location if this is a desired request of the client. Equation (15) requires that the window allocated to a grid point should cover some portion of the grid to which it has been allocated by the binary variable z_{im}. This ensures that the allocated grid point and its associated data are not far away from the position of the window:

$$\sum_i z_{im} \geqslant 1 \quad \forall m \in M_r, \forall r \in RR : \beta_{mr} = 1, \tag{13}$$

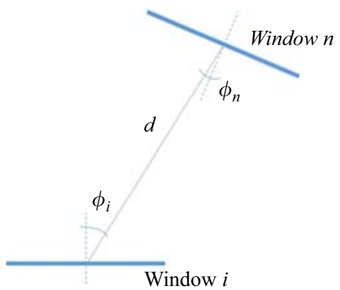


Figure 2. Angles between windows and neighbouring points

$$\sum_{i} z_{im} = 1 \quad \forall m \in SR, \tag{14}$$

$$\left|x_i - t_m^x\right| + \left|y_i - u_m^y\right| \leqslant \max\{T_m, U_m\} + FF(1 - z_{im}) \quad \forall i \in 1, \ldots, |M|, \forall m \in M, \tag{15}$$

2.2.3 Window non-overlap constraints. If two or more windows are located then it must be ensured that they do not overlap. The following equations are defined to achieve this:

$$\left|x_i - x_j\right| \geqslant 0.5\left(W_i + W_j\right) \cdot \mu_{ij}^x \quad \forall i, j \in 1, \ldots, |M| : i \neq j, \tag{16}$$

$$\left|y_i - y_j\right| \geqslant 0.5\left(L_i + L_j\right) \cdot \mu_{ij}^y \quad \forall i, j \in 1, \ldots, |M| : i \neq j, \tag{17}$$

$$1 + \mu_{ij}^x + \mu_{ij}^y \geqslant z_{im} + z_{jn} \quad \forall i, j \in 1, \ldots, |M| : i \neq j\ \forall m, n \in M. \tag{18}$$

Equation (16) states that no overlap can occur in the horizontal x direction, if $\mu_{ij}^x = 1$. Equation (17), on the other hand, specifies that no overlap can occur in the vertical y direction, if $\mu_{ij}^y = 1$. Equation (18) requires that either of Equation (15) or Equation (16) holds if two windows i, j are located on the façade of the building.

2.2.4 Glazing system constraints. If a window is located then it must have a glazing system associated with it. This is done with the help of the following equation:

$$\sum_{g \in G} \gamma_{gi} = z_{im} \quad \forall i \in 1, \ldots, |M|, \forall m \in M \tag{19}$$

2.2.5 Domain of variables. The domain of the variables is defined by the following equations:

$$L_i, W_i, x_i, y_i \geqslant 0 \quad \forall i \in 1, \ldots, |M|, \tag{20}$$

$$z_{im}, \gamma_{gi}, \mu_{ij}^x, \mu_{ij}^y \in \{0, 1\} \quad \forall i, jc1, \ldots, |M| : i \neq j, \tag{21}$$

3. Solution approach

In this section, we present the solution approach adopted to solve the proposed WLP. The first approach discussed relies on associating an *a priori* preference to each objective function. The second approach is based on solving a bi-objective problem, where the trade-off between two contrasting objectives is analysed.

3.1 Lexicographic optimisation

Since the WLP is multi-objective in nature, no single point will optimise all the incorporated objective functions at once, knowing that the objective functions are conflicting. The concept of optimality, adopted in single objective models, is thus replaced with that of Pareto optimality (Censor, 1977). Assuming a minimisation problem, a solution of a multi-objective optimisation problem, $z^*$is a Pareto optimal if there does not exist another feasible solution $\bar{z}$ such that $f_e(\bar{z}) \leqslant f_e(z^*) \quad \forall e \in O$ and $f_m(\bar{z}) \leqslant f_m(z^*)$ for at least one index $m \in O$, where O is the set of objective functions solved in the multi-objective problem. In other words, a solution is Pareto optimal if no Pareto improvement is possible.

Many approaches exist in the literature to solve the multi-objective optimisation problem. In this paper, we adopt the lexicographic approach because it is common for designers to have a preference defined over the optimised objective functions. Prioritising the objectives to be solved means that a unique solution of the Pareto hyper-surface exists (Kerrigan and Maciejowski, 2002). Lexicographic optimisation has been implemented extensively in the literature as a favourable approach in many engineering applications (Ehrgott, 2013).

Assuming that all objective functions are transformed so that they are minimised, a solution which is a lexicographic minimiser of the WLP is one where the objective function being minimised at a given stage of the lexicographic process can only be reduced at the expense of at least one of the higher-prioritised objectives. This is shown in the following algorithm:

Algorithm 1.
Lexicographic optimisation:

$f_1^* = min_{x \in X} f1(x)$
 for $n = 2,\ldots,0$
  $f_n^* = min_{x \in X} \{f_n(x): f_p(x) \leqslant f_p^* \ \forall p = 1, \ldots, n-1\}$
 end for
 Lexicographic minimiser:
  $x^* \in \{x \in X: f_p(x) \leqslant f_p^* \ \forall p = 1,\ldots, 0\}$

The general notation adopted for the lexicographic optimisation process is given by the term *lex* min$[B_v, B_w]$, which indicates that the model is first solved by minimising the highest ranked objective, B_v. Once an optimal solution is yielded, the model is re-solved by adopting B_w as the objective function and by including the constraint $B_v \leqslant B_v{}^*$ in the model, where $B_v{}^*$ is the optimal solution of B_v obtained at the initial stage. The final solution is that attained once all $|B|-1$ objective functions have been included as constraints, where B is the set of all objective functions involved in the model.

3.2 The ε-constraint method

The augmented ε-constraint approach is adopted (Mavrotas, 2009) to obtain non-dominated solutions on the Pareto front. The ε-constraint approach works best if there are two to three objective functions, because anything higher than that would result in difficulty in visualising the associated Pareto front.

The procedure involved in the augmented ε-constraint method can be summarised as follows:

(1) lexicographic optimisation is used to obtain a payoff matrix out of the objectives involved (Ehrgott, 2013);

(2) one of the objective functions is then converted into a constraint;

(3) the payoff matrix is used to define the right-hand side (RHS) of the converted constraint;

(4) non-dominated solutions are obtained by varying the RHS of the converted constraint; and

(5) a slack variable is added to the constraint to convert it into a binding one; the slack variable is also included in the objective function which is optimised.

4. Case study

In this section, the proposed optimisation model is examined on a realistic case study. Figure 3 displays the building examined, which is a residential villa located in Dubai. Dubai is located on the northern coastline of the United Arab Emirates and is known to be a global city and

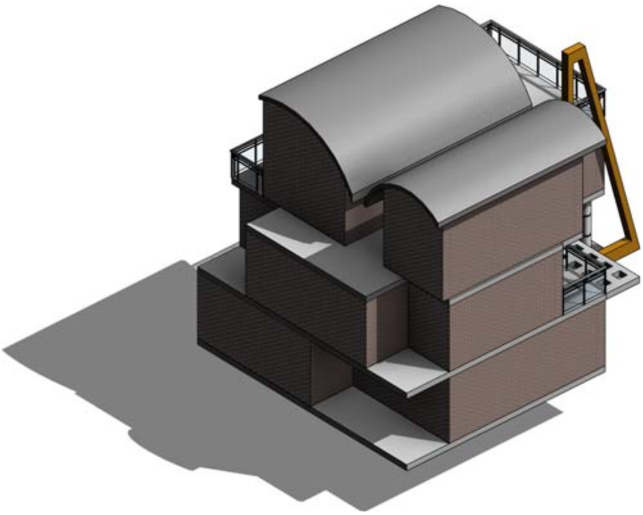


Figure 3.
Case study analysed

business hub of the Middle East. Dubai has a hot desert climate, where temperatures in the Summer can reach an average high of 42°C (Dubai Meteorological Office, 2017).

Overall, three scenarios are examined in this section: Scenario 1 involves optimising the location, glazing system and sizing of windows for the building shown in Figure 3, while addressing all four criteria listed above, using lexicographic optimisation. In Scenario 2, a bi-criteria analysis is adopted whereby two contrasting objectives are optimised and their Pareto front is reported. Scenario 3 reports the optimisation result for two other cities located in the MENA region and contrasts the solution with that of Dubai. For brevity purposes, only one side of the building's façade is chosen for optimising the positioning of the windows. The process is easily generalisable for all faces of the building envelope.

The neighbouring dwelling surrounding the residential building under consideration is shown in Figure 4.

Results in this section rely on the following input data:

- Orientation of the building is southwest.
- Window shape is assumed to be rectangular/square. The shape of the window, as proven by Acosta *et al.* (2016), should not have an influence on the energy consumption of a building and as such it is not included as a decision variable in our proposed model.
- Prices of window installation were collected after contacting a number of suppliers in Dubai.
- The U-value and solar heat gain coefficient for windows of different glazing were obtained from local suppliers.
- Two surrounding residents are identified. These are located at 15 and 27 m, respectively, away from the southern side of the building façade.
- The residential building is assumed to house five occupants with Central VAV, HW Heat, Chiller 5.96 COP, Boilers 84.5 eff installed as the HVAC system. The exterior envelope of the building comprises of double brick walls with an expanded polystyrene insulated timber frame roof supporting ceramic roof tiles.
- ΔT is taken as 20°C (Table II).

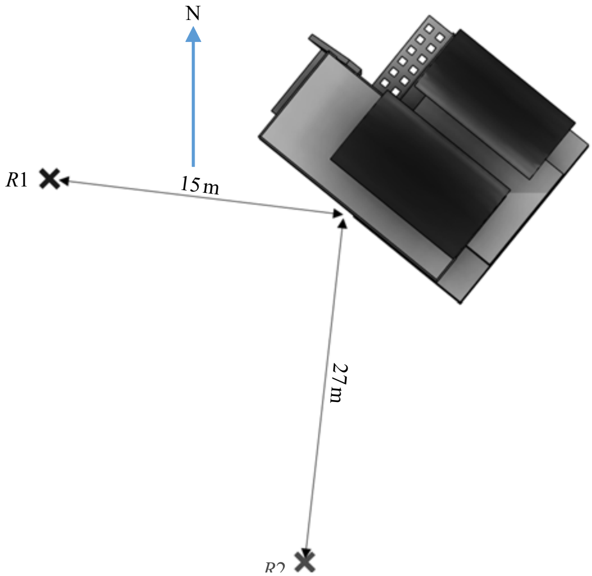


Figure 4. Plan view indicating close-by neighbours, where R1 is Neighbour 1 and R2 is Neighbour 2

Table II. Glazing systems examined and corresponding coefficients

System	Solar heat gain	*U*-value
1	0.81	5.6
2	0.39	2.1
3	0.45	5.9
4	0.6	3.6
5	0.26	1.3

The problem is formulated in GAMS (GAMS Development Corporation, 2013) where Couenne is adopted as the solver (Belotti, 2009). GAMS is an algebraic modelling language that allows for the programming of optimisation problems and the use of various optimisation solvers. It is adopted in this study due to its versatility and encompassing solvers that can be implemented on a range of mathematical programming problems. The problem is coded on a personal computer running on Windows 10 as the operating system with 3.4 GHz and 16 GB of RAM. Solution times were all less than 200 s.

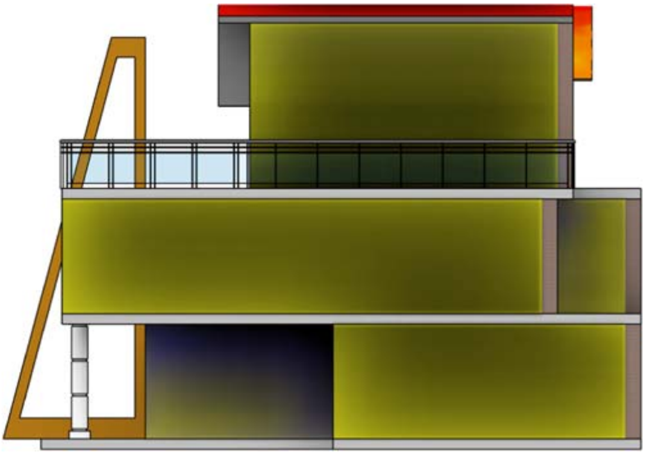
4.1 Optimisation results through lexicographic optimisation

In this section, the solution obtained by applying a lexicographic optimisation approach to the proposed model to solve the case study is analysed. For the first set of computation experiments conducted, the case study is solved such that the objectives are ranked according to their order of appearance in the model, i.e. $B_3 \succ B_1 \succ B_2 \succ B_4$, where the relationship $a \succ b$ highlights the preferential ranking of a in comparison to b. The WLP is solved over four stages, where emphasis is placed on increasing privacy at the first stage, B_3; this is justifiable as it is a critical factor in the MENA region. Second preference is given to minimising heat gain through the windows in order to combat the climatic conditions of the MENA region, B_1. The third preference is then assigned to maximising daylight to ensure a passive design, B_2. Finally, the monetary cost of window installation is included as the fourth and final objective in the last stage of the lexicographic optimisation, B_4.

A solar analysis was run on the building and the results indicated that the side with most radiation is the southern side. The solar analysis is performed in Green Building Studio (Autodesk, 2017). As a result, the southern face of the building is chosen as the plane on which windows are to be optimised (Figure 5). The southern façade was then discretised as shown in Figure 6. Each grid point was associated with a solar radiation measure.

The number of grids chosen to discretise the building façade is based on balancing solution quality and computation time. It is important to note that that the size of all girds do not need to be equal. In the case examined, the optimum number of grids that allowed for a balance between computation time and solution quality was 62 girds, as can be seen by the sensitivity analysis conducted in Table III.

Table IV displays the evaluation of the criteria optimised through the lexicographic optimisation approach.



Note: Blue indicates the lowest solar radiation level while red is associated with the highest level

Figure 5.
Solar analysis

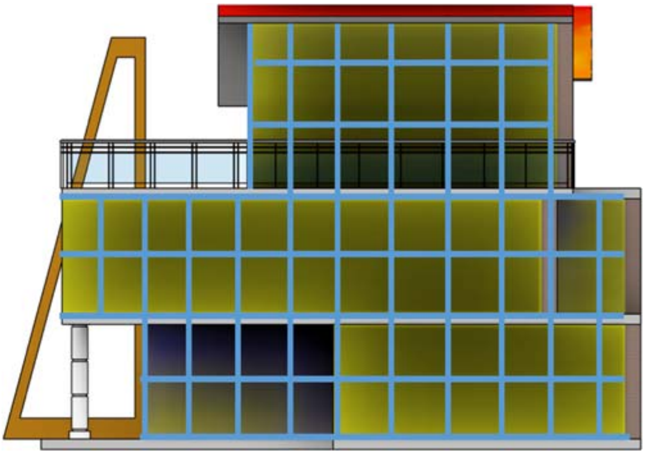


Figure 6.
Discretisation of southern side of the building façade

Given that the first step of Algorithm 1 minimises the privacy criterion, B_3, the solution at this stage yields a window layout that is associated with the highest level of privacy. The average cumulative level of privacy from all located windows is measured at 0.13. The other criteria (B_1, B_2 and B_4) are all evaluated at the optimised solution for B_3. It is important to note that heat gain, as given by the value of B_1, is relatively low for the first stage (maximum possible heat gain is around 4e6 W). This is due to the fact that the privacy criterion forces the size of the windows to be minimised. At the same time, given the small size of windows, the daylight criterion is associated with a low value, because its value is not the one being optimised at this stage. The small sizes of windows induce a relatively small cost to be associated with window installation, as noticed by the value of B_4. Given that in the first stage the privacy criterion is the one that is optimised, this results in a small number of windows being installed with small dimensions.

At the second stage, the model is optimised for B_1 (solar heat gain), with the conversion of objective B_3 to a constraint. The privacy criterion is already at its minimum value at the second stage of the optimisation process. Only a 5 per cent drop ensues in the value of B_1; this is attributed to the fact that the first stage of the optimisation already produces windows that are small in size. Any additional improvement in the value of B_1 is attributed to the change in the locations of the windows on the facade and the utilisation of better glazing to ensure that solar radiation is low. In terms of the daylight criterion, B_2, it decreases by 17 per cent at the second stage; because the heat gain criterion is minimised, this forces the size of the windows to decrease even more relative to the first stage. The cost of window installation increases by 84 per cent in the second stage, relative to the first stage. This is attributed to the fact that glazing systems with higher solar heat gain coefficient, and which happen to be more expensive, are now adopted for the windows to decrease their solar heat gain.

At the third stage of the optimisation, the daylight criterion is optimised, B_2. This leads to larger windows being adopted compared to the first two stages. The cost of window installation naturally increases because the number and size of windows installed now increase.

At the final stage of the optimisation, the cost of window installation is still the same as its value at Stage 3, even though the focus at this stage is on minimising installation costs. No further reduction in cost is possible since the size and glazing system of the windows cannot be altered given the constraints imposed on B_3, B_1 and B_2.

Number of grids	Average deviation from solution obtained at 100 girds (%)[a]	Average computation time (s)
34	38	22
46	24	39
58	14	123
62	9	220
74	7	432

Note: [a]Average across all objective functions

Table III. Sensitivity analysis to choose optimum number of discretised grids

	B_3	B_1 (Heat gain – Watts (W))	B_2 (Daylight factor %)	B_4 (\$)	No. of windows	Maximum size of window (m)
lex min [B_1]	0.13	2.2e + 6	1.8	20,567	4	1.3 × 1.8
lex min [B_1, B_2]	0.13	1.9e + 6	1.5	37,765	4	1.2 × 1.7
lex min [B_1, B_2, B_3]	0.13	1.9e + 6	2.2	56,819	7	2.3 × 2
lex min [B_1, B_2, B_3, B_4]	0.13	1.9e + 6	2.2	56,819	7	2.1 × 2

Table IV. Lexicographic optimisation with order $B_3 \succ B_1 \succ B_2 \succ B_4$

For the case study used, the best solution over all stages of the lexicographic optimisation for Criteria B_3, B_1 and B_2 is obtained at the stage for which the respective function is optimised. Due to the gradual constraints imposed onto the model, the objective function values remain stagnant once they have been optimised at their respective stage within the lexicographic optimisation procedure.

The final layout of windows is that yielded by the last stage of the optimisation process, the results of which are displayed in Figure 7. As can be seen, four windows are positioned at the lower level of the building; at this level, the visibility of these windows to surrounding neighbours is the lowest and hence the criterion measuring the privacy of the dwelling is maximised. At the same time, the lower left portion of the façade is the area with the least solar radiation and hence any solar gain from windows placed in this area will be minimal. The window located at the top level is positioned in a region where solar energy is relatively low compared to the rest of the façade at that respective level. A study room was located at that end of the building and so a window needed to be placed for the study room.

During the optimisation runs, it was noticed that an influential impact on heat gain was the positioning of the window on the façade. In particular, for low solar heat gain, the model places windows in the lower left portion of the façade where total solar radiance from the sun is assessed to be the lowest. Another location that is associated with low solar radiance is that which is positioned at the higher end of the façade closer to the roof. This is due to the shading effect of the roof which lowers the solar radiation incident on the façade.

4.2 Bi-objective analysis

To demonstrate the conflicting nature of the WLP examined in this paper, in this section, a bi-objective analysis is conducted, through solving the problem using the ε-constraint approach. The analysis is performed on the case study above between criteria that are most conflicting in order to reveal the resulting trade-off. The first set of results, shown in Figure 8, is obtained by contrasting the daylight criterion, B_2, against the heat gain criterion, B_1.

As can be seen in Figure 8, the trade-off curve is positively slanted with an S-shape, indicating that at higher daylight factors, the rate of increase of heat gain decreases in comparison to its rate of increase at lower daylight factors. This is attributed to the fact that the computation of the daylight factor is directly related to the area of the window; the larger the area of the window, the greater the daylight factor. At the same time, as the area of the window increases, the solar gain that results will also increase.

Figure 7.
Window layout based on lexicographic optimisation

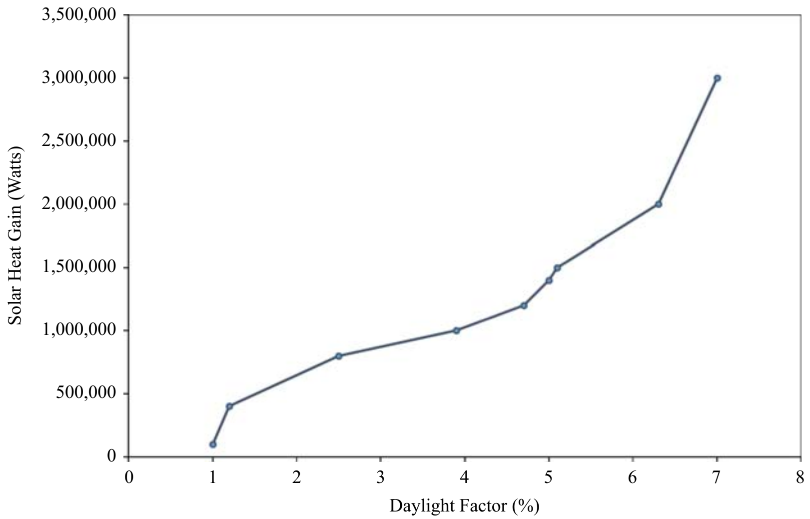


Figure 8.
Trade-off between heat gain and daylight factor

Figure 9 shows the trade-off curve between the privacy criterion B_3 and the daylight criterion B_2. As is noticed, the trade-off curve is now more concave in shape, compared to the one in Figure 8, indicating that the rate of increase of visibility is greater than the rate of increase of the daylight factor for the majority of the solution points that lie within $2 <$ daylight factor < 6. The relationship is still one that is increasing, highlighting that as the visibility decreases (privacy increases), the daylight factor drops. This makes sense as the windows are expected to decrease in number and in size in order to increase the privacy measure.

The trade-off between cost of window installation and daylight factor is shown in Figure 10. The relationship is now more linear, indicating that the rate of increase of cost of installation and daylight factor is almost proportional. The cost of installation is highest when a large number of large-sized windows are installed. This results in the highest

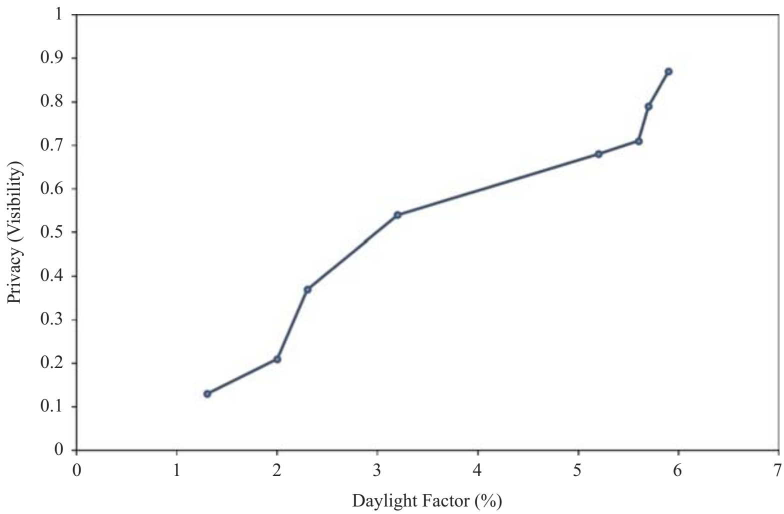


Figure 9.
Trade-off between visibility (measure of privacy) and daylight factor

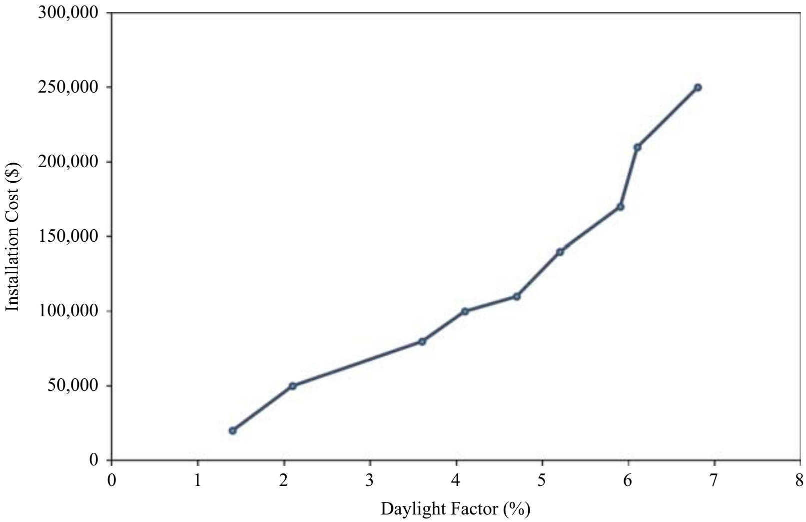


Figure 10.
Trade-off between installation cost and daylight factor

daylight factor since more solar light can passively enter the building. On the other hand, the least cost installation results when a layout is associated with small number of windows and small dimensions.

4.3 Optimised results for three cities in the MENA region

In this scenario, the case study above is run assuming the same building is located in three different cities in the MENA region, namely Dubai, UAE; Doha, Qatar; and Kuwait City, Kuwait, all known to have extreme hot weather during the Summer. The orientation of the building was fixed in the southwest direction in all cities considered. Only two objectives are considered in this scenario, namely the daylight factor and total heat gain, in order to reveal the Pareto front between these two contrasting objectives, through the use of the ε-constraint method. The solar analysis is again performed in Green Building Studio after specifying the locations of the cities (Autodesk, 2017). The optimised front for all the cities is shown in Figure 11.

It is important to note that in the case that a low daylight factor results, due to the low number and small dimension of the windows placed, the solar gain for all cities is going to be almost the same, at around 500,000 W during the cumulative analysis. Once the window size increases, the Pareto front for each city starts to deviate from one another. For the highest level of daylight factor, the solar gain is largest in Kuwait. The reason for this is quite clear; the solar radiance in Kuwait is higher than in both other countries (Islam *et al.*, 2009). As a result, for any given daylight factor, the resulting solar heat gain in Kuwait will always be larger than that of Dubai and Doha. Doha comes in second after Dubai; the climate in Dubai is known to be highly humid in comparison to the other countries and hence solar radiance is lowered via the presence of a higher moisture content in the air (Kazem *et al.*, 2012).

5. Final concluding remarks

A novel problem was proposed and solved in this paper for the location of windows on facades of residential buildings. Multiple objective functions that conform to the MENA region were formulated and solved through the use of both lexicographic optimisation and

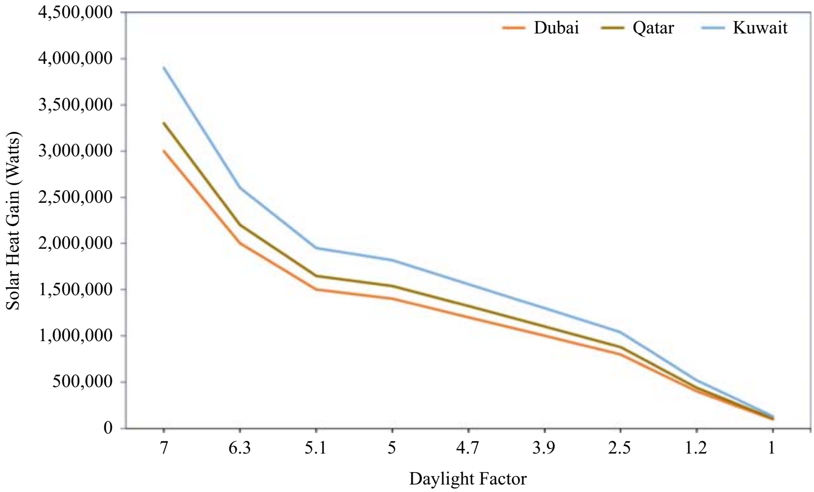


Figure 11. Optimised trade-off curve for all cities considered

the ε-constraint approach. The criteria optimised included the solar heat gain, the daylight factor, the visibility of the window to surrounding residents and the cost of window installation. A simulation tool, namely Green Building Studio, was utilised to get the total solar radiance incident onto the surface of the building. The outer façade of the building was then discretised, with each discrete location associated with a single solar radiance value. This produces discrete sets of values to approximate the total incident solar radiation onto the façade of the building. The problem was formulated as an MINLP, and solved using an exact approach for a realistic case study. Variables considered in the model include the dimensions of the window, the glazing type, the number of windows to include and the location of the windows.

The results analysed the trade-off present in the criteria optimised. It was found that a window layout where preference was assigned to maximising the privacy of the house led to a solution with lowest daylight and solar heat gain. It was also shown that the cost of installation varied by almost 172 per cent through a lexicographic optimisation procedure where the first preference was associated with visibility, and last preference was assigned to the cost of installation. The size and the location of the window were found to impact the heat gain, day light and privacy of the house. An analysis on various cities within the MENA region also indicated the dependence of the results obtained on the climatic condition of the city. Dubai was found to have a low solar heat gain compared to Kuwait and Doha due to its high humidity rates in Summer.

The proposed model provides an opportunity for automating the decision-making process when it comes to deciding an appropriate location for windows on building facades. Since multiple objectives are considered, the trade-off between the different objectives can be realised through constructing the Pareto optimal curve, which only considers efficient solutions.

The weakness of the model lies in its combinatorial nature which causes the model to become intractable as the number of the discretised grids used increases. This is why there is a need for the modeller to find a reasonable balance between number of grids and solution time. An analysis such as the one conducted in Table III helps reveal the trade-off.

The model has been designed for hot climates in the MENA region. However, through slight modification, the problem can also be adopted for cold climates. In cold climates the emphasis will be on maximising direct sunlight that passes through windows and the glazing system adopted to permit greater heat trap and hence minimise heat loss through the exterior envelope of the building. In particular, Equation (19) can be modified to encompass the need for maximising the glazing of windows to allow for greater heat trap in cold climates.

This research presents a tool that can act as a decision support system for architects when it comes to deciding on the locations of windows on the exterior walls of a building. It presents an automated approach to optimise such a decision-making approach. Through the utilisation of multiple objectives, the approach also presents an opportunity to examine the trade-offs that ensure from such decisions made, particularly with regards to privacy, solar heat gain and daylight factor. The approach proposed in this paper can therefore be used in the early design stages to enable architects to realise the impact of locations chosen for windows on privacy, solar heat gain and the daylight factor. Conventional simulation models are time consuming and hence should only be adopted at the final stages to validate the design decision made earlier on. In addition, the use of the trade-off analysis between various important criteria permits the decision maker to make a choice that suits the preference aligned in the designs. In particular, designers in the MENA region can make use of the model in their residential building design to determine the sizing, location and glazing of windows on building facades that results in a sustainable building.

Future research can build on to this by examining other related architectural problems and methods for optimising the decision making involved. The authors are exploring other avenues in terms of optimising space allocation and exterior envelope building material composition.

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