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Optimisation of building shape and orientation for better energy efficient architecture

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Abstract

Purpose – This paper aims to optimise building orientation in Tehran, as well as determining the impact of its shape, relative compactness (RC) and glazing percentage on its optimised orientation.

Design/methodology/approach – A cubic module was used and a set of 8 of the same module with 16 different formations were analysed for their orientation (360°), the RC (four groups) and the amount of glazing percentage (25, 50 and 75 per cent).

Findings – The results show that the optimised orientation of a building in Tehran strongly depends on its passive solar heat gain elements, their orientation and their position in building; furthermore, glazing percentage amount, amongst the studied factors, plays the most important role in determining a building's orientation.

Practical implications – The application of the findings of this study in Tehran city planning and also technical details of buildings will lead to a great energy saving in construction sector. Furthermore, the deployment of the proposed design guidelines in construction has explicitly been proven to save a prodigious amount of energy.

Originality/value – The main research question is taken directly from authors' initiative when working as university professor and research associate. The case study buildings, their morphological configurations and sustainable features have not been presented before in an academic journal.

Keywords Solar energy, Correlation analysis, Simulation, Optimisation, Regression, Orientation, Energy efficient architecture, Glazing percentage, Shape

Paper type Research paper

1. Introduction

The development of technologies and industries has led to an unprecedented need for fossil fuels, and the demand and the irrational energy consumption has put this entity in danger. Furthermore, with regard to the ever-growing population all over the world, the critical role of energy resources has dramatically increased (Taylor *et al.*, 2014); therefore, there has been an emphasis on the identification of new energy resources which can have an inevitable impact on economic and environmental advancements (Zhang *et al.*, 2013; Pacheco *et al.*, 2012; Saadatian *et al.*, 2012). Another reason why more prominence has been put on renewable energies is the adverse effect of carbon emission by using fossil fuels: global warming and climate change.

Sun is one of the invaluable energy assets (Panwar *et al.*, 2011) which has been the centre of attention in the past few decades (Dür and Nowak, 2009). In the late twentieth

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and twenty-first centuries, many countries have been contemplating potential ways of replacing non-renewable energies through solar energy.

Optimisation has also been considered as a way of reducing energy consumption (Vanderbei, 2001; Madsen and Langthjem, 2001; Fowler *et al.*, 2004; Quaglia *et al.*, 2014; Jeong-Tak and Jae-Weon, 2014) which has been sensed necessary for the use of energy in the building sector. Consequently, energy efficient architecture was raised as a response to this issue of minimising the negative environmental impact of buildings (Roshan *et al.*, 2012; Li *et al.*, 2013). One aspect of energy efficient architecture is the way a building loses and gains heat. Energy efficient architecture also suggests optimisation and energy-saving strategies through defining optimised orientation, shape, compactness, window to wall ratio (WWR), etc. which play a major role in the overall amount of energy a building loses or gains (Pacheco *et al.*, 2012).

2. State of issue

In a country with rich resources of fossil fuel reserves like Iran, energy consumption is one of the highest in the world. However, there is still a potential to apply building regulations to minimise the usage of fossil fuels. According to the Iranian national building codes office declaration in 2002, the energy consumption in constructions accounts for more than one-third of the total energy use in the country (Daryushi, 2015). Consequently, the critical role of architecture in achieving energy efficient targets is undisputable.

According to Granadeiro *et al.* (2013a), a building loses heat through different ways:

(1) transmission through walls, windows, doors, floors, roofs, etc.;

(2) heat loss generated by ventilation; and

(3) heat loss caused by infiltration (due to leakages in the building construction, opening and closing of windows, the air in the building shifts, etc.) and gains heat through:

- mechanical equipment such as air-conditioners;
- solar radiation; and
- internal gains.

This paper studies the role of orientation, shape, compactness and building's degree of transparency concerning the amount of energy it loses or gains when reinforced with both active and passive solar heat gain elements (PSHGEs) on an isolated generic case building in the capital city of Iran, Tehran, and proposes guidelines for designing buildings in the regions with the same climatic conditions as Tehran.

Several studies have investigated potential consequences of a building's orientation, R_c and transparency degree on its overall energy use over a course of a period of time such as Marks (1997), Depecker *et al.* (2001), Jedrzejuk and Marks (2002a), (2002b); Pessenlehner and Mahdavi (2003), Ourghi *et al.* (2007), Sok Ling *et al.* (2007), AlAnzi *et al.* (2009), Albatici and Passerini (2010), Catalina *et al.* (2011), Faizi *et al.* (2011), Albatici and Passerini (2011), Ihm and Krarti (2012), Granadeiro *et al.* (2013b) and Quaglia *et al.* (2014).

Catalina *et al.* (2011) studied the influence of a building's shape on energy demand. They studied 12 case buildings for various shapes and glazing areas to figure out the relation between them and thermal consumption. Two factors that were used to define building geometry are building shape factor (L_b) and relative compactness (R_C). L_b is the ratio between the heated volume of the building and the sum of all heat loss surfaces. R_C is the volume to surface ratio of a building compared to the most compact shape with the same volume. They concluded that the impact of building shape factor is more important for hot climates with higher solar radiation and outdoor temperature values.

AlAnzi *et al.* (2009) analysed the impacts of building shapes on energy efficiency of buildings. The method they used correlated the annual energy use to the relative compactness (R_C) as an indicator of building shape, WWR and glazing type (SHGC). Several buildings with the same number of storeys and floor area but with different floor plan were studied. The research found out that when there is no window, the energy use in the building, independent of its form, is proportional to $1/R_C$. A building with 50 per cent WWR showed the same trend; however, the trend proved to be dependent on the building shape. They also argue that the orientation of a building has an impact on its energy performance, and this impact is almost independent of the building shape especially for low WWR values.

Sok Ling *et al.* (2007) examined the effects of geometric shapes on the total solar insolation gained by buildings in hot humid climate. Ecotect program was used to study the variations in width-to-length ratio and building orientation. The main findings can be summarised as the following: the vertical wall receives the most solar insolation, circular plan with W/L ratio 1:1 is the optimum geometric shape and the highest level of daily average solar insolation is received on the east wall, followed by the south, west and north walls.

Faizi *et al.* (2011) made research by simulation study on a building using Ecotect program. Their results suggest that the ratio of width to length along the North should be minimised, south-facing walls should be maximised and the most translucent layers should be considered on south, east, west and north sides.

Depecker *et al.* (2001) studied the relationship between the heating consumption and the shape of a building. To make variations in the shape coefficient (the external skin to inner volume ratio) of their 14 case buildings, they chose to study different configurations with the same volume as opposed to studying the same shape and making its dimensions vary with the same proportions. Their results illustrate that energy consumption is inversely proportional to the compactness in case of cold severe scarcely sunny winters.

Pessenlehner's and Mahdavi's research (2003), whose methodology is the closest to this paper, evaluated the reliability of a compactness indicator for energy-related evaluative assessments given that buildings with the same compactness attribute could differ in enclosure transparency, orientation and morphology. The research simulated the heat consumption of 54 morphologically different buildings which were made of 18 cubical modules and were categorised based upon their relative compactness value, and also with different glazing scenarios. Results show that both larger glazing areas and more compact shapes lead to slightly lower heating loads.

Although the material in the literature has greatly covered the issue, the lack of a thorough approach towards the matter of energy consumption which considers the main factors of shape variation, R_C, glazing and orientation can be observed; for instance, all above-mentioned research works studied only passive performance of buildings with a limited number of shape variations. Some such as Catalina *et al.* (2011), Faizi *et al.* (2011) and Depecker *et al.* (2001) did not consider WWR as a parameter, and

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some like Pessenlehner *et al.* (2003) did not study case buildings with higher than 50 per cent glazing amount. This study takes a step forward and evaluates a relatively high number of buildings with shape, glazing, R_C and orientation difference exploiting both active and PSHGEs such as solar windows, Trombe walls and solar collectors.

3. Methodology

A building's orientation, shape or configuration and compactness (Albatici and Passerini, 2010; Albatici and Passerini, 2011) are amongst the most important factors in determining its eco-friendliness:

- *Orientation:* According to Ghobadian (2006), a building in Iran is best oriented east-west. The length of the building should be oriented to the south because it gains the most solar energy in the winter and can be protected by a shade from the summer heat. East and west façades, gaining a significant amount of energy during summer, should be minimised and are best protected by adjacent blocks and vegetation.
- *Shape:* Ghobadian (2006) adds that in summer, during which solar radiation is almost vertical, the roof of a building receives more solar energy than other sides. Likewise, the south façade gains more solar energy in winter due to the inclination of solar radiation. Generally, cold weather necessitates compactness and excessive solar radiation means being stretched in the east-west ward. The best configuration is the one that loses the least energy in winter and gains the least energy in summer. (Kasmaee, 2006) Therefore, the importance of shape is more stressed, and the optimised configuration in relation with the building's optimised orientation has been studied in this paper.
- *Relative compactness (R_C):* Following the previous paragraph, a square plan is the best option, as it provides the most volume to envelope ratio. However, according to Kasmaee (2006), this applies to old buildings with small openings that little amount of solar radiation penetrating through its openings can be neglected. This conclusion can be debated about contemporary buildings which enjoy large areas of glass façade (Kasmaee, 2006). Olgyay argues that determining the best formation for contemporary buildings should be based upon the influence of air temperature and solar radiation on indoor thermal conditions (Kasmaee, 2006).
- *Glazing percentage (WWR)L:* Glazing percentage stands for the amount of the glazing area to the area of the wall which is very effective in the heat transfer of buildings. In case this amount is reduced, less heat will be transferred outside (heat loss) (National Building Code Office, 2007). On the other hand, greater percentage of glazing lets more solar radiation in which leads to a greater heat gain. Although it is the main source of natural lighting, there should be an optimal amount so that the amount of heat loss is minimised. Windows, because of low thermal resistance (R) compared to the other parts of buildings' envelop, should not be located in undesirable and cold fronts of the building (National Building Code Office, 2007).

3.1 Research questions

The research aims for finding a response to the following questions through the below explained methods:

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RQ1. What is the optimised orientation for a typical building in Tehran? (Figure 1)

RQ2. Do buildings with different shapes but with the same relative compactness or R_C have different optimised orientations? In other words, does shape affect optimisation in orientation? If yes, what formation is more energy-efficient? (Figure 1)

RQ3. How can the difference in relative compactness affect the optimised orientation? What is the relation between a building's compactness and its optimised orientation?

RQ4. Does glazing percentage make any difference in the optimised orientation of the same building with the same shape and R_C? (Figure 1)

Each case building and groups are analysed for their optimised orientation with studying the relationship between their optimised orientation and their shape, relative compactness (R_C) and glazing percentage (WWR).

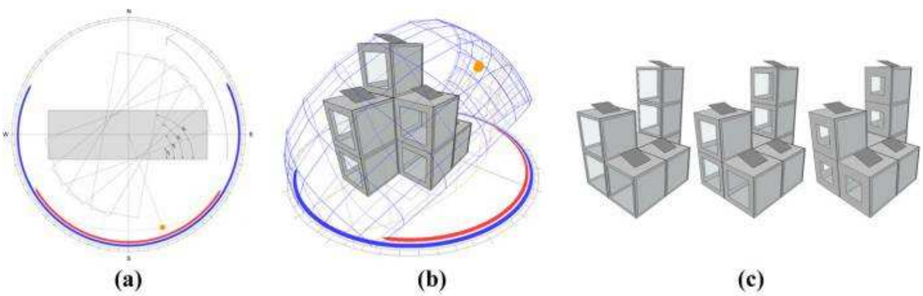
3.2 Assumptions

Some parameters remained unchanged through the simulations such as location (Tehran, Iran), building volume (64 m^3) and internal heat gains. Invariant assumptions regarding thermal transmittance which directly relate to the material of the building are summarised in table of materials.

3.3 Hypothesis

According to the precedent studies, east-west-oriented buildings are considered to be the most efficient ones in terms of the difference between the amount of energy they gain through sun light and the energy they lose (Ghobadian, 2006). A research by Faizi *et al.* (2011) on a residential complex in Tehran suggests that the studied models should have the lowest ratio of width to length and also the maximum level of south-facing walls (Nasrollahei *et al.*, 2013).

It is predicted that the optimised orientation angle would be a slight deviation (most likely to the East) from the South.



Notes: (a) How orientation affects the amount of energy a building receives; (b) a formation of eight modules and its position to the annual and daily sun path; (c) three different glazing percentage amounts (75, 50 and 25 per cent) of a selected case building
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Figure 1. Research objectives

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3.4 Performance analysis simulation

The impacts of four above-mentioned parameters on the energy performance of chosen case buildings (Table III) are simulated with the help of a commercially available software package which was developed by added codes. It offers a wide range of simulation and building energy analysis functionality that can improve performance of existing buildings and new building designs within the context of its environment. Whole building energy analysis, thermal performance, water usage and cost evaluation, solar radiation, day lighting and shadows and reflections are amongst the parameters that can be evaluated in this software. This paper is focused on thermal performance.

3.5 Research domain

The research is structured around two major research domains; one concerning its perspective towards the concept of house and one regarding simulation scale.

House as an influential issue in human being life depends on lots of determining factors such as social, environmental, economic, etc. This paper focuses on energy consumption through schematic design management perspective.

Regarding these sorts of software packages, they respond very well in micro scales in contrast to macro scale. Fluids' behaviour varies from micro to macro scales. Energy simulation software put assumptive censors based on how accurate the user wants it to perform. The trend line of temperature, heat consumption, and other variables that each of these censors record does not necessarily represent the overall changes that occur in that space. This is due to the fact that many more parameters such as humidity, air flow or radiation affect the temperature of each point which can be greatly different from point to point. For instance, solar radiation to a window might increase the temperature of a specific point in the space near a censor which leads to a higher temperature record by this censor. However, the heat from the solar radiation can lead to convection of the warm air and as a consequence of this movement of the air a momentary decrease in the temperature of a point in the space near which a censor is located happens. These differences in recording information can be seen as jumps in the trend line which can be interpreted at a micro scale, but at a macro scale, which is the approach of this paper, these sorts of jumps do not have a meaning. At the macro scale, the trend line moves very smoothly and without any great discrepancies from the adjacent data. This error is called "scale error" that cannot be solved and occurs because of the mathematical and geometrical nature of the censors which have no dimensions as opposed to a point in the real world.

In the following diagrams, there can be seen some points whose value has dramatically jumped. Such points have been ignored in this study because they appear to be results of a scale error. We have overlooked micro changes, as the changes that happen in micro scale are instantaneous changes and do not convey the flow of the diagram or the total temperature variation diagram.

3.6 Error control

Small indentations are due to errors in software and do not concern the scale error which was explained earlier on. Due to the fact that the main objective of this paper is optimisation, software error and the difference between the examined data and real data do not affect final findings. The aim of this paper is to figure out which formation, orientation degree, glazing percentage or relative compactness is more efficient;

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therefore, difference matters. Moreover, periodical errors of starting-up the software which can happen every time the software runs are also overlooked.

4. Case buildings

The data that show the relation between the shape and energy consumption rate can be seen on a diagram representing a trend line (Depecker *et al.*, 2001). To identify the shape, a shape "coefficient" should be defined which is normally, in energy-related research, the relation between a building's envelop and its volume (Depecker *et al.*, 2001; Pacheco *et al.*, 2012):

$$L_b = V \times A^{-1}$$

(Depecker *et al.*, 2001; Pessenlehner and Mahdavi, 2003).

A is the envelope or the external skin and V is the inner volume. In other words, the L_b indicates the amount of compactness of a building. L_b (or characteristic length) (Pessenlehner and Mahdavi, 2003) depends on the shape's size that is absolute value of the volume. It contrasts to the relatively newer shape coefficient R_C which is purely shape-dependant. The R_C is the normalised version of the L_b which can be obtained by dividing the L_b of a building by the L_b of the most compact building shape with the same volume (Table II):

$$R_C = \frac{(V/As)\text{Building}}{(V/As)\text{Ref}}$$

(Pacheco *et al.*, 2012; AlAnzi *et al.*, 2009; Ourghi *et al.*, 2007).

Following the above determined coefficient, the study of the buildings has been conducted with comparing different shapes with the same volume (Table III), as opposed to a second scenario which would be considering a given shape and making dimensions vary in the same proportions (Depecker *et al.*, 2001).

A modular geometry system was derived based on an elementary cube with specification given in Table II. It has two Trombe walls (which are PSHGEs) on south and east sides, and two windows on west and north sides. The fact that two Trombe walls are selected and inserted on two adjacent sides of the base cube is its easing nature for time parameter (Sadineni *et al.*, 2011). In other words, Trombe walls neutralise extreme heat and cold weather conditions (Saadatian *et al.*, 2012) for different building usages such as office buildings and residential which have different operating hours and also make simulations time-independent. These characteristics make Trombe walls suitable for being inserted in a general building with no specified future use. The Trombe walls are on adjacent sides because the author expects that they cover east to south and south to west side of the building which represent the best sides for locating a Trombe wall (Abbassi *et al.*, 2014) and worst sides for openings.

To achieve variation in internal transparency, glazing amount (WWR) was changed. Regarding the glazing area, three levels were regarded, 25, 50 and 75 per cent, as a fraction of the corresponding exterior wall (Figure 1). Windows are double glazed with aluminium frame Figure 2, Table I.

To generate different building shapes, eight such elements were used (Table II) (Pessenlehner and Mahdavi, 2003). Table II represents the most compact form created

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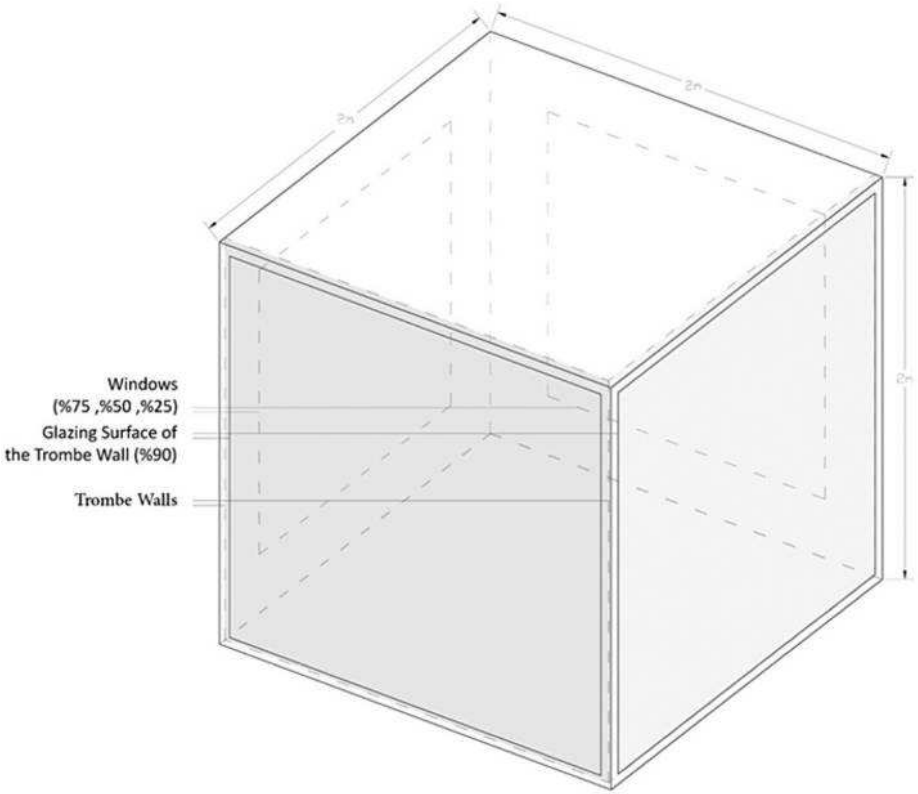

Figure 2.
The elementary cube representing its PSHGEs (Trombe walls and solar windows)

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Table I.
Materials and their unique features used in the cubic module

Roof/ceiling	100 mm concrete + 75mm extruded polystyrene insulation	U-value: 1.49 W/m2.K
Walls	200mm heavy weight concrete + 25mm extruded polystyrene insulation +25mm stucco	U-value: 0.85 W/m2.K
Trombe wall	250mm heavy weight concrete	U-value: 0.9 W/m2.K
Floor	200mm heavy weight concrete + 5mm carpet underlay + 15mm carpet	U-value: 0.92 W/m2.K
Glazing type	Double glazed_ Alum Frame	U-value: 6 W/m2.K SHGC (0-1): 0.94
Solar collector	Electrical efficacy (%): 12	Space heating efficacy (%): 42
Infiltration rate (ach)	0.50 air change rate	
Wind sensitivity (Ach/hr)	0.25 air changes/hour	
Thermal comfort (C)	18-25 degree centigrade	

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with all these cubes. The modules were arranged in different ways to create 16 different formations which fall into 4 categories based on the R_C (Table III).

4.1 Reference prototype

Volume: $8 \times 8 = 64\ m^3$; Envelope surface: $16\ m^2 \times 5 = 80\ m^2$ (Table II).

Moreover, each building has four solar collectors each with $1\ m^2$ area that accounts for $4\ m^2$ area of active solar heat gain elements. Each solar collector is faced south with its altitude being 18 degrees.

4.2 Studied models

Table III.

5. Experiment

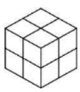
Each shape is rotated with the increment of 1 degree for 360 degrees and is analysed in each orientation to find the best orientation, shape, glazing percentage and R_C. Given 16 shapes which fall into 4 categories of relative compactness, 3 glazing options and 360 orientations, a total of 17,280 variations were generated for simulations. Models are studied based on the energy they gain, the one they lose, and the net gain and the results are illustrated in separate diagrams.

Models illustrate similar behaviour in energy simulation when characterised with the same WWR (glazing percentage). For 25 per cent glazing area, models fall into one category while two groups with the same behaviour can be distinguished with buildings with 50 per cent glazing area. Ultimately, when it comes to 75 per cent of glazing area, buildings portray dramatically different behaviour in comparison with the two previous modes, and they can be divided into three different categories. Therefore, in the experimental diagrams below, the glazing percentage is assumed as the invariant factor. All three diagrams of Gain, Loss and Net Gain follow a smooth trend, while there can be seen some radical jumps from the normal move in, for example, Loss diagrams which are because of the scale error that was described earlier.

5.1 25 Per cent glazing diagrams

Figure 3 shows the three mentioned diagrams for 25 per cent glazing area. In Figure 3 (Gain), as the building rotates from 0 degrees onwards, its solar gain amount do not significantly change until it reaches 40 degrees angle in which point it starts to decrease the solar energy it gains. It continues with the same reaction to the angle increase until 60 degrees which is nearly the turning point. In this point, the gained energy starts to slow down until it reaches its minimum which varies between 161 and 177 for the 16 case studies. As the building starts to gradually face westwards, it increases the energy it

Table II. The reference prototype representing the most compact formation of the 8 cubic modules

Description	Module	Morph	R_C	L_b
Reference prototype surface area = $80m^2$	8 cubes of $2 \times 2 \times 2$ m		RC = (V/As) Building/(V/As) Ref = 1	$V \times A\text{-}1 = 64/80 = 0.8\ m^2/m^3$

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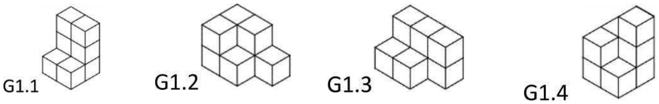
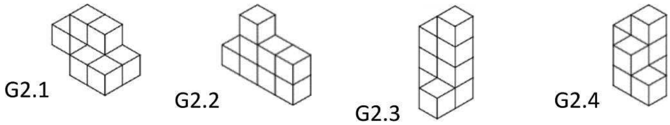
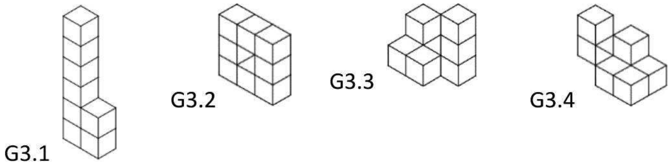
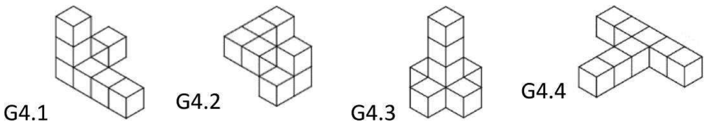
Group	Morph
G1: Envelope surface area = 112 m^2 R_C = 0.85 L_b = 0.57 m^3/m^2	 G1.1 G1.2 G1.3 G1.4
G2: Envelope surface area = 120 m^2 R_C = 0.80 L_b = 0.53 m^3/m^2	 G2.1 G2.2 G2.3 G2.4
G3: Envelope surface area = 128 m^2 R_C = 0.75 L_b = 0.50 m^3/m^2	 G3.1 G3.2 G3.3 G3.4
G4: Envelope surface area = 136 m^2 R_C = 0.70 L_b = 0.47 m^3/m^2	 G4.1 G4.2 G4.3 G4.4

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Table III. Chosen models categorised in four groups based on their R_C

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gains with almost the same rate, as it lost energy before the minimum point. According to the simulations' data, the Gain diagram reaches its maximum somewhere between 308 to 320 degrees in different case studies.

In the Loss diagram (Figure 3), which happens for all case studies the same way, the buildings start to lose more energy, as they rotate counter clockwise from 0 degrees until the diagram reaches its maximum which ranges between 141 to 160. The degree in which the case study loses minimum energy is between 358 to 7 degrees, nearly horizontal.

The Net Gain diagram (Figure 3), which is the most important one in this study because it determines the best orientation of the building by illustrating the angle at which a building receives the most energy overall, depicts nearly the same behaviour as the Gain diagram. The diagram, which represents a trend line resembling a sine wave, indicates that the best orientation for the 16 case studies with 25 per cent glazing percentage is where the trend line reaches its maximum and the worst orientation is where it reaches its minimum. According to the output data, the best orientation for such buildings is between 308 to 318 degrees and the worst one is between 155 to 175 degrees.

5.2 50 Percentage glazing diagrams

Case studies with 50 per cent glazing percentage show a slightly different behaviour than the previous group when analysed. Their diagrams fall into two categories that are summarised below (Figures 4-6). The differences in the diagrams of the two categories are discussed in the following paragraphs:

- *Category 1:* G1.1, G1.2, G1.3, G2.1, G2.2, G2.3, G3.2 and G3.4.
- *Category 2:* G1.4, G2.4, G3.1, G3.3, G4.1, G4.2, G, G4.3 and G4.4.

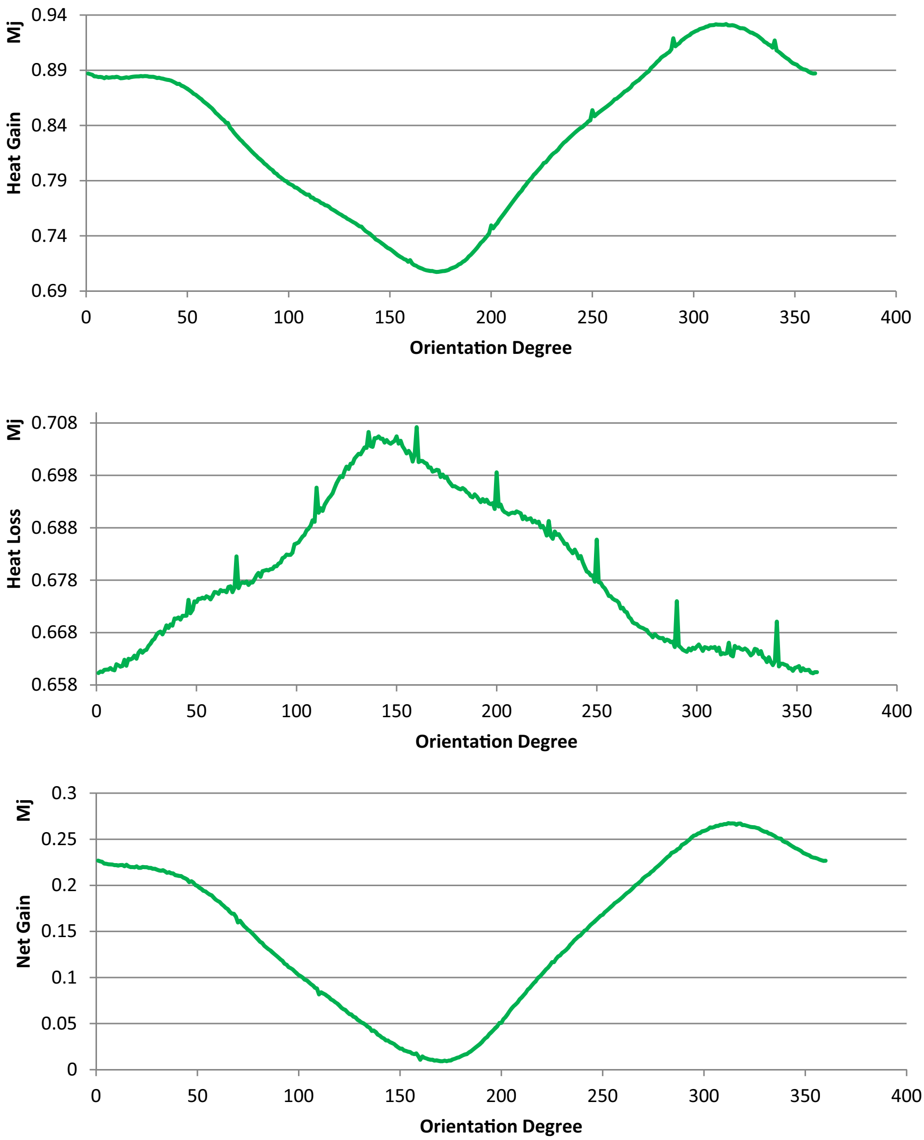

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Figure 3.
G1.1_25 per cent "Gain", "Loss" and "Net Gain" diagrams

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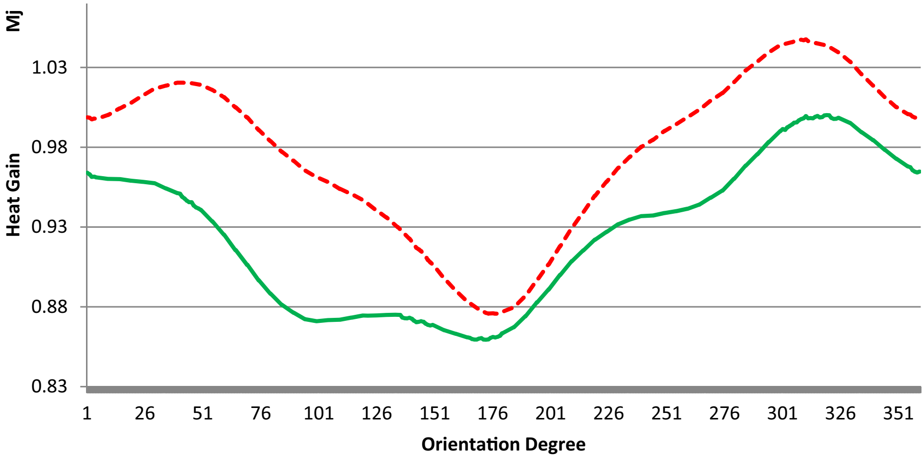

Figure 4.
G1.1 (red-dashed line) and G1.4 (green solid line) 50 per cent "Gain" diagram

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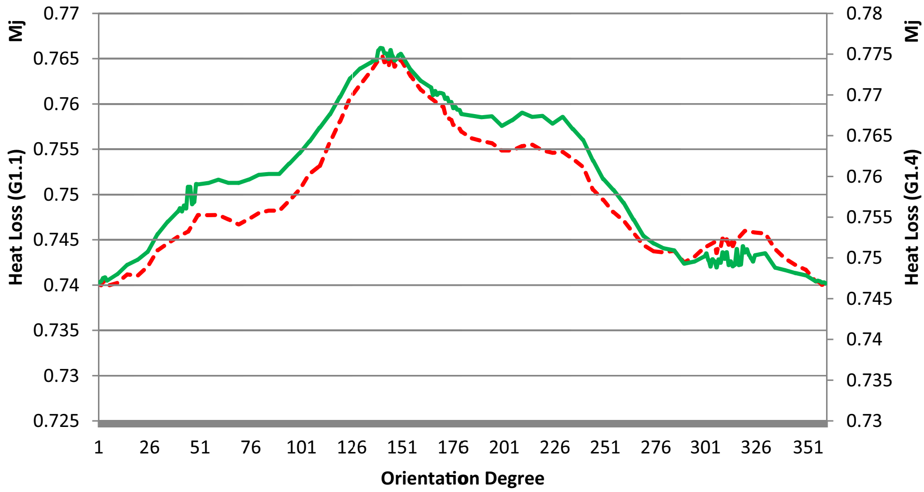

Figure 5.
G1.1 (red-dashed line) and G1.4 (green solid line) 50 per cent "Loss" diagram

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In the Gain diagram of the first category (Figure 4 – red-dashed line), the building starts to receive more energy until it reaches 40 degrees while in the previous case, there was not a major change in gained energy. Past the 40 degrees point, the trend is reversed and the building starts to receive lesser and lesser energy until the diagram is at its minimum. As the building rotates, the energy it gains increases before the trend becomes downward again at the maximum point. The Gain diagram of the second category (Figure 4 – green solid line), on the other hand, does not have major fluctuations before it experiences a drop from 30 degrees point to 90 degrees

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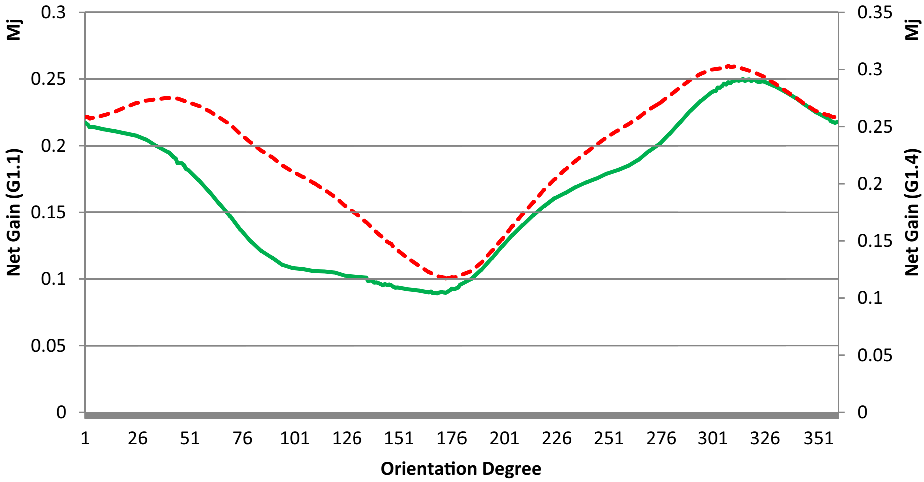

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Figure 6.
G1.1 (red-dashed line) and G1.4 (green solid line) 50 per cent Net Gain diagram

point, and then, it has no significant fluctuations until 140 degrees point. Moreover, the increase rate of the trend line slows down to almost zero at 250 degrees point before it starts to increase again until it reaches its maximum. The diagram of 50 per cent glazing area is maximised at 293-320 degrees and minimised at 173-178 degrees depending on the studied case building.

The Loss diagram of the first category (Figure 5 – red-dashed line) resembles the one for 25 per cent glazing area. As the building rotates, the loss amount increases until it is at 50 degrees where there cannot be seen much difference in the amount of lost energy. The trend line starts its move again from 90 degrees point before it reaches its maximum. On the way to its minimum amount, the trend line has a nearly constant move between 200 and 230 and an upturn at 290 degrees point from which point the trend goes upward until 330 degrees and then continues its downward move before it reaches its minimum. The Loss diagram of the second category (Figure 5 – green solid line) is almost the same as the first category apart from the almost straight move between 290 and 330 degrees points which was an upturn in the diagram of the first category. The maximum point of this diagram happens between 136 and 145 and its minimum between 358 and 7 degrees depending on the studied case.

Figure 6 shows the Net Gain diagrams of the first and the second categories. They are almost the same as their Gain diagrams; therefore, the paper suffices to mentioning the best orientation degree for them which varies between 299 and 317 and the worst orientation degree which varies between 168 and 177.

5.3 75 Percentage glazing diagrams

The studied buildings with 75 percentage glazing area show a noticeably different behaviour between themselves and also in comparison with the previous groups. The diagrams of the 16 case buildings fall into three different categories which are listed below (Figures 7-9). Similarities and differences are described in the following paragraphs:

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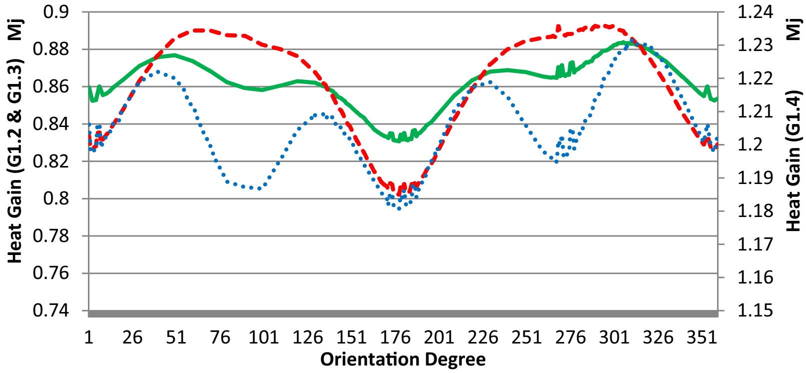

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Figure 7.
G1.3 (red-dashed line), G1.2 (green solid line) and G1.4 (blue-dotted line) 75 per cent Gain diagram

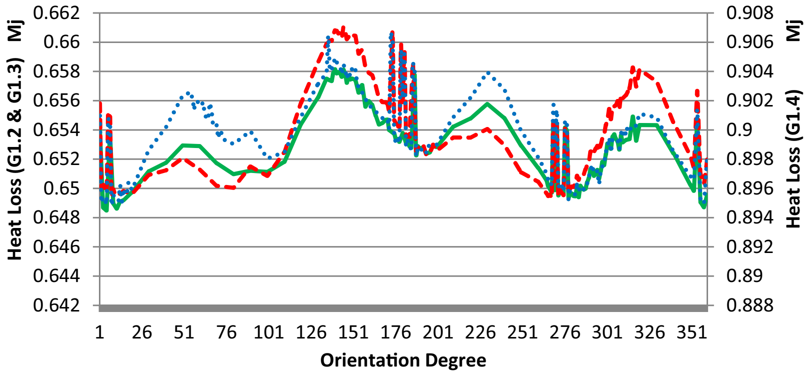

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Figure 8.
G1.3 (red-dashed line), G1.2 (green solid line) and G1.4 (blue-dotted line) 75 per cent Loss diagram

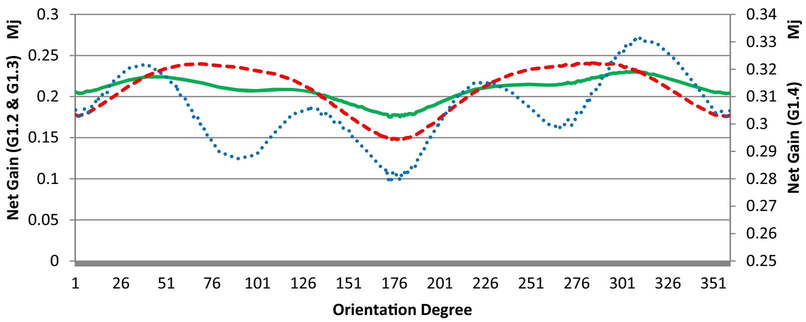

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Figure 9.
G1.3 (red-dashed line), G1.2 (green solid line) and G1.4 (blue-dotted line) 75 per cent Net Heat Gain diagram

- *Category 1:* G1.1, G1.3, G2.1, G2.2, G3.2 and G3.4.
- *Category 2:* G1.2, G2.3, G2.4, G3.1, G3.3, G4.1 and G4.4.
- *Category 3:* G1.4, G4.2 and G4.3.

Figure 7 (red-dashed line) illustrates the Gain diagram of the first category. It is noticeable that the gain amount rises very sharply in comparison with the previous Gain diagrams until it reaches the 60 degrees point. From this point on, the amount starts to decrease with a low steep before it starts to drop from 120 degrees point to the minimum amount with a higher coefficient of the trend line. In Figure 7 (green solid line) which depicts the Gain diagram of the second category, the point at which the upward move reverses happens almost at 50 degrees. On the way to the minimum point, an upturn happens from 100 degrees point to 120 degrees point, and then the trend line goes to its minimum with the same steep as the trend line of the first category. The trend line of Figure 7 (blue-dotted line) which is the Gain diagram of the third category has more radical ups and downs than the second category's diagram. It reaches its first peak at 40 degrees point and starts to gain less solar energy before it reverses its trend line at 90 degrees point. Like the diagram of the second category, it experiences an upturn, but this time between 90 degrees point and 135 degrees point before its trend line drops between the 135 degrees point and its minimum amount. Due to the fact that all diagrams in the group of 75 per cent glazing area have a nearly symmetrical trend line, a mirror of what was described happens from the minimum point to the end. The minimum happens at 178 degrees and the maximum happens at 303 degrees.

Figure 8 illustrates the Loss diagram of the three categories with 75 per cent glazing area. All three represent the same move but with greater differences between top and bottom points; therefore, only the Figure 8 (red-dashed line) is described. As the building rotates, the energy it loses increases until 50 degrees points at which the trend line moves downward for the next 25 degrees. Then, the loss amount increases radically to the maximum point which would be between 140 and 145 degrees. Past the maximum point, the loss amount decreases up to 200 degrees point where the trend reverses again and the loss amount increases until it reaches 230 degrees point. Again the loss amount starts to decrease until 268. The trend line then rises up until 320 before it goes down again.

Figure 9 shows the Net Gain diagrams of the first, the second and the third categories, respectively. They resemble their Gain diagrams; consequently, the paper suffices to mentioning the best orientation degree for them which varies between 270 and 312 and the worst orientation degree which varies between 173 and 179:

- Comparing the diagrams of the studied models with 75 per cent glazing area with the ones with less transparency, it is observed that the diagram has been multiplied in "y" direction; therefore, it can be said that the trend line coefficients are higher.
- The diagrams of case buildings with 75 per cent glazing amount are nearly symmetrical; therefore, it can be said that the energy received by walls with higher amount of glazing are comparable with the energy gained by Trombe walls. For 75 per cent glazing area, different behaviour from different models are observed that they suggest a wider range of optimised orientation which is also

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probably mainly because of high percentage of glazing area that can provide a comparable solar gain source with Trombe walls.

6. Discussion

The data of the experiments are evaluated to find the relationship between the R_C, formation difference and glazing percentage to orientation and finally the optimised orientation of the studied models; therefore, they are categorised in a way to study only one parameter at a time by omitting a variant from the comparisons. This bivariate data analysis necessitated to use scatterplots to describe the direction, form and strength of the relationship between the two quantitative variables. The regression line also gives a compact model of overall pattern.

Figures 10 and 11 indicate the amount of maximum gain and maximum net gains for all cases each with three glazing percentage area of 25, 50 and 75 per cent, as they rotate 360 degrees. Each dot, in Figure 10 diagram, for example, has the value of the gain amount of the corresponding case. As it is obvious, in most cases, the gain amount increases when moving from 25 to 50 per cent and also from 50 to 75 per cent which accounts for the windows be a passive solar gain element even comparable with Trombe walls when having a higher amount of glazing percentage. The regression line has a slight negative slope which indicates less gain amount for later cases.

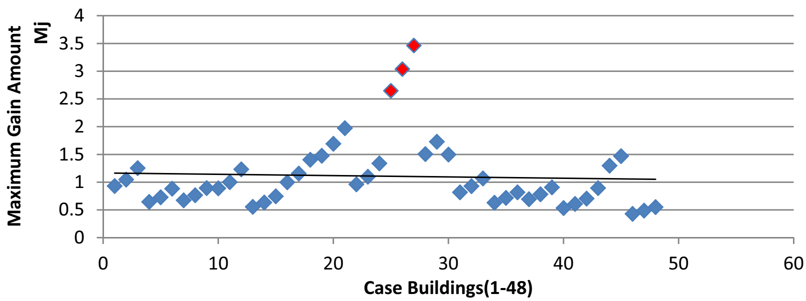

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Figure 10.
Maximum Heat Gain amount of all studied buildings

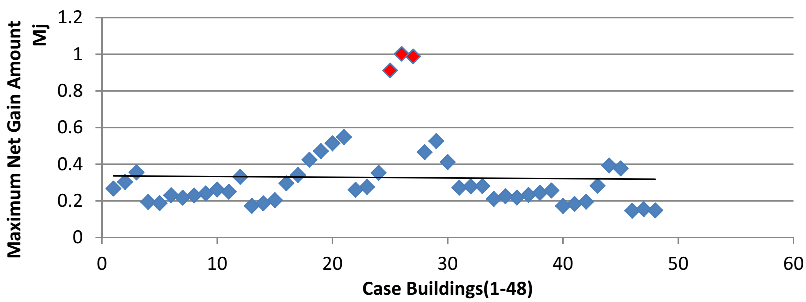

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Figure 11.
Maximum net heat gain amount of all studied buildings

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Some case studies have higher residuals (which are the distances between their output data from performance analysis and the regression line) like Case G3.1 which can be interpreted as the error of the software; therefore, the results from the ninth experiment are neglected for the study. They tend to weaken the relationship between the two variables and also the R^2, but the results can be more exact once defining a standard deviation. If we overlook the results from the Case G3.1, it can be concluded that there is a strong relationship between the two variables, as the dots are concentrated around a line.

6.1 R_C and optimised orientation

Figures 10 and 11 are not any help in extracting specific results due to the number of variant parameters. To determine the relationship between the R_C and the orientation of the buildings, we have studied the models with the same glazing percentage separately, so we actually have omitted the glazing percentage parameter from the studies. Figure 12 depicts the relationship between the R_C and orientation for case buildings with 25, 50 and 75 per cent glazing, respectively.

Observing the previous three figures, it can be seen that the results are more scattered from the regression line once we move from Figure 12 (25 per cent) to Figure 12 (50 per cent) and Figure 12 (75 per cent). This shows that by increasing the amount of glazing, the strength of the relationship between the R_C and orientation decreases.

Earlier in this study, it was said that according to Olgyay, the relationship between the R_C and energy consumption only applies to buildings with lesser amount of openings. To validate the relationship between the R_C and orientation for 25 per cent glazing, χ^2 distribution has been used. Table IV shows the actual data in one row and the author's assumption in the other. For the first group, the Number 314 (the average of the four orientation degrees for four buildings) has been determined, and for the next groups, 2 degrees has been added for the assumed orientation (according to the hypothesis, buildings with less R_C are prone to lose more energy and then need to be oriented more to the south-east to receive more energy).

As a result of the above data, $\chi^2 = 1$; therefore, the above-mentioned hypothesis is valid for the studied buildings with 25 per cent glazing percentage. As a result, it is recommended that designers consider the R_c as a decisive factor for buildings with low

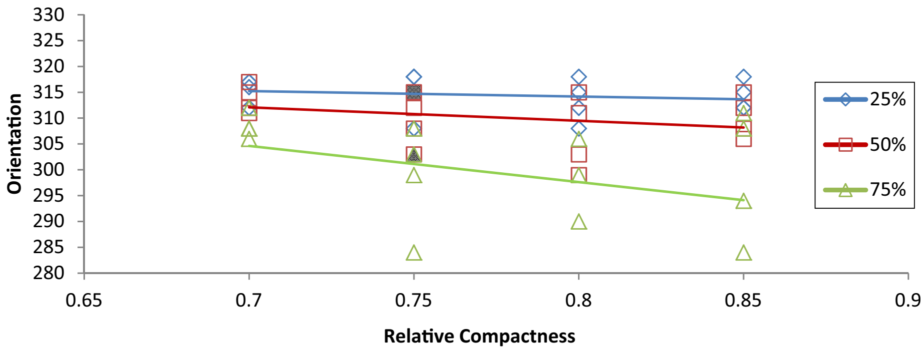

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Figure 12. Orientation to R_C for the cases with 25, 50, and 75 percentage glazing area

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glazing amount and be aware of a building's high R_c as an indicator of its high level of energy efficiency and vice versa. Following the relationship between the R_C and orientation, it can be concluded that when the R_C decreases, the overall vector of PSHGEs (Figure 21) of the building need to face more to the east to gain more solar energy.

6.2 Shape and optimised orientation

To analyse the relationship between building formation and its optimised orientation, the data are compared between the buildings with the same R_C and same glazing percentage. Figures 13-16 illustrate the optimised orientation of G1-4 buildings, respectively, in three colours for three glazing percentage variations. Evaluating all four diagrams, not much data can be extracted from them; therefore, there cannot be any results regarding the relationship between the shape and the optimised orientation.

Having analysed above diagrams, it can be argued that shape difference does not make a difference in energy performance of buildings with the same R_c, letting designers create innovative building shapes with a careful attention to their R_c.

6.3 Glazing percentage (WWR) and optimised orientation

The impact of the glazing percentage on the buildings' orientation can be observed on several diagrams such as Figures 10 and 11, and also in Figures 17 and 18 which represent all 16 case buildings with 3 different glazing percentage amounts and their relationship between them and their optimised orientation.

Table IV.
Actual and predicted orientation degree of 25% glazing amount buildings

Data category	G1				G2				G3				G4			
Actual orientation degree	312	318	312	315	312	308	318	315	318	308	318	315	312	317	316	317
Assumption (expected data)	314	314	314	314	316	316	316	316	318	318	318	318	320	320	320	320

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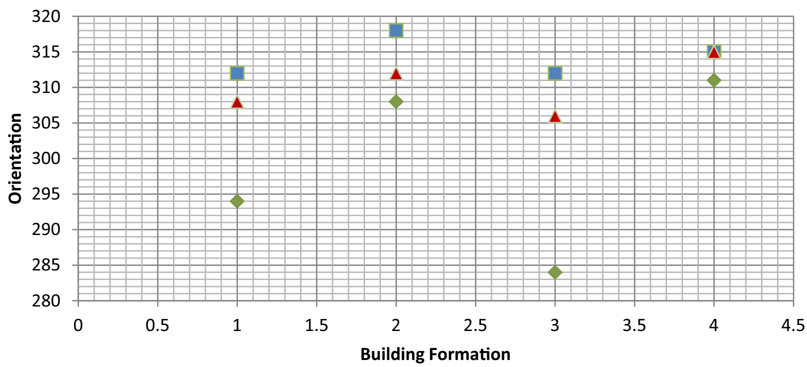

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Figure 13.
The optimised orientation of the G1 (R_c = 0.85) buildings (blue 25 per cent, red 50 per cent and green 75 per cent glazing)

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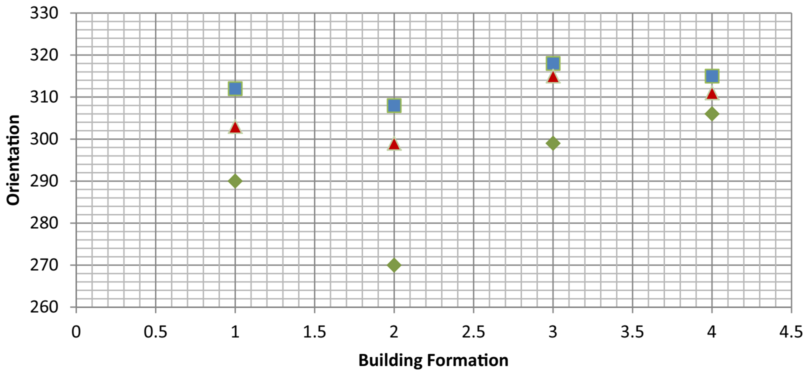

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Figure 14.
The optimised orientation of the G2 ($R_c = 0.80$) buildings (blue 25 per cent, red 50 per cent and green 75 per cent glazing)

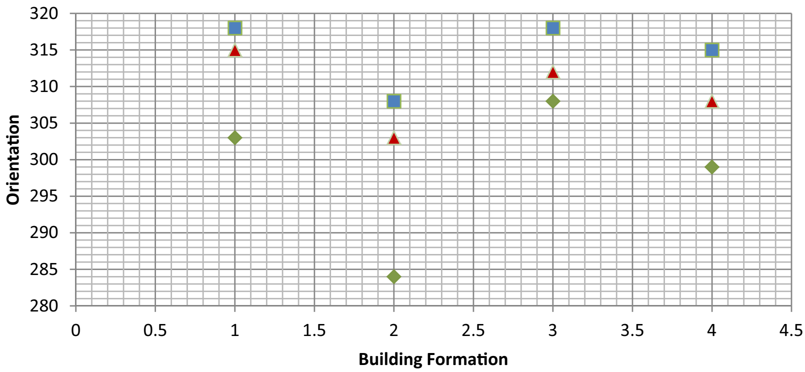

Figure 15.
The optimised orientation of the G3 ($R_c = 0.75$) buildings (blue 25 per cent, red 50 per cent and green 75 per cent glazing)

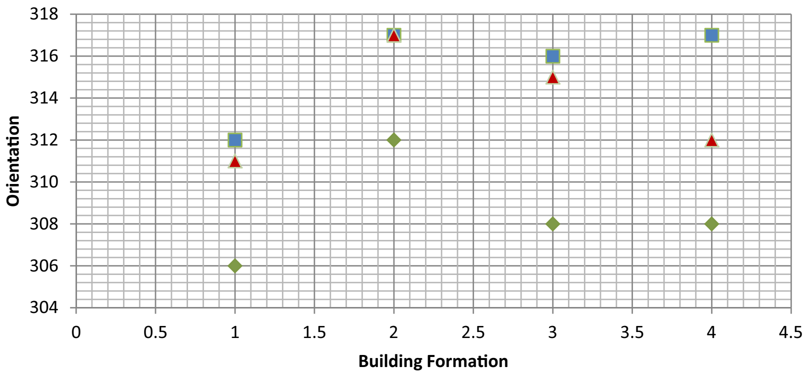

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Figure 16.
The optimised orientation of the G4 ($R_c = 0.70$) buildings (blue 25 per cent, red 50 per cent and green 75 per cent glazing)

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As it can be seen in Figures 10 and 11, as the glazing percentage increases, the amount of the Gain and also Net Gain increases, which proves that larger openings act as PSHGEs. Moreover, orientation degree decreases.

In Figures 17 and 18, every three points which are connected with solid lines are three glazing percentages of the same shape. Dotted lines are the connection of two different buildings. As it can be seen, as the glazing percentage increases, the optimised orientation for the building decreases. In fact, it can be interpreted that buildings with smaller window sizes need to orient more to the south-east to gain more solar energy. Figure 21 illustrates how glazing amount affects optimised orientation.

Figure 19 outlines the role of glazing percentage in design. According to it, buildings with less glazing amount need to orient the overall vector of their PSGHEs towards the south, and as the glazing amount increases, they incline more to the west so that their solar windows can absorb more heat from morning and afternoon sunlight.

6.4 Optimised building orientation

Optimised orientation can be determined studying the scatterplot diagram which represents the orientation at which a building reaches its maximum gain minus its heat loss in the y axis, and studied models (1 to 48) in x axis. The optimised orientation for 48 studied models range from 270 to 318, which is a broad range for prescribing as the best orientation range; therefore, the average and standard deviation from the average have been calculated to reach a more precise range. The average degree of all 48 orientation

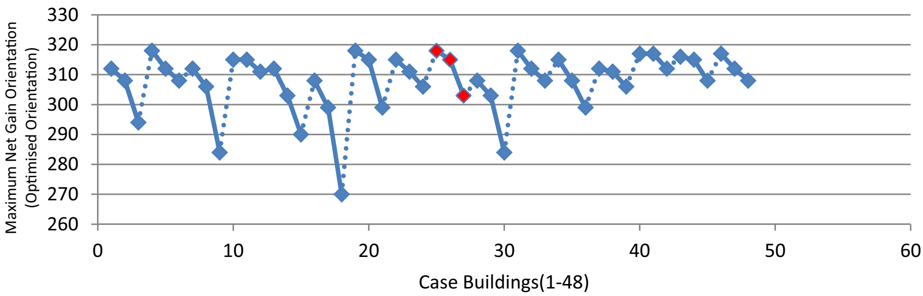

Figure 17. Maximum net gain orientation and its relation with glazing amount

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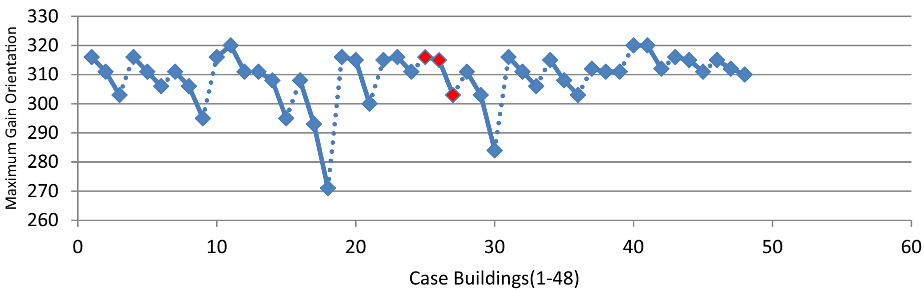

Figure 18. Maximum "Gain" orientation and its relation with glazing amount

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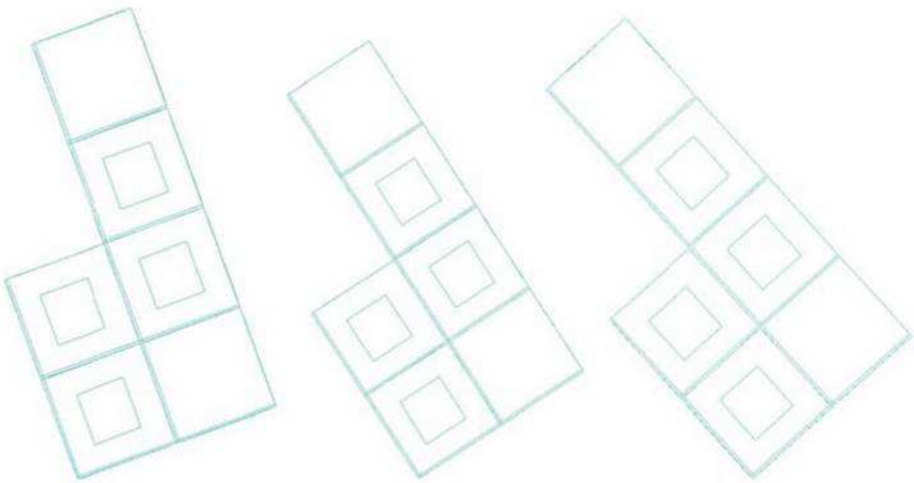

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Figure 19. Case G2.1 with 75, 50 and 25 per cent of glazing amount posed at their optimised orientation

angles is 307.97, and the standard deviation is 9.94; consequently, the optimised building orientation ranges from the average minus the standard deviation (298 degrees) and the average plus the standard deviation (318 degrees) Figure 20.

Some other points that are extracted from evaluating the data and diagrams are:

- All Net Gain diagrams have the same trend as the Gain diagram. In other words, net gained energy reaches its maximum when the model is oriented to the direction from which it gains maximum solar energy.
- The research results show that the optimised orientation for the studied models is between 298 and 318 degrees (which is south-west to south). This shows the hypothesis has not been proven right, which says maximum gain happens when

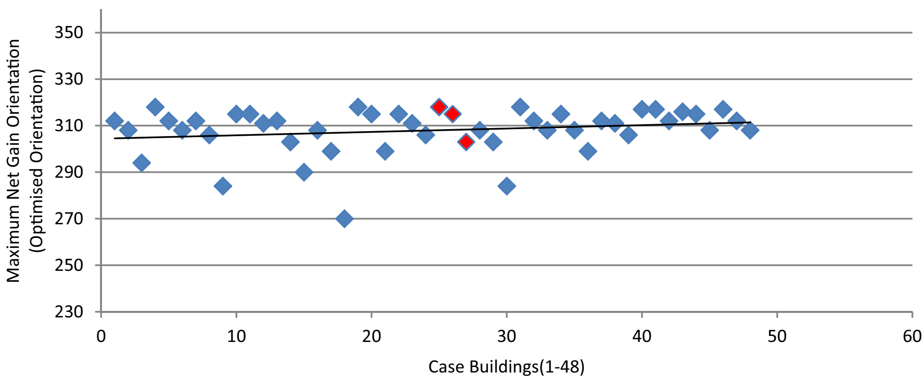

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Figure 20. Optimised orientation of all studied buildings

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facing south to south-east wards (Kasmaee, 2006), based on the precedents and the paper's hypothesis; however, considering unique characteristics of the module which has two Trombe walls on the east and south sides and two windows on the north and west sides, it can be concluded that the optimised orientation happens when the overall vector of PSHGEs of the module face south to south-east wards (Figure 21). In other words, the optimised orientation range which has been obtained as a result of this study is almost 45 degrees more than when the building oriented south to south-east ward, and this is exactly the degree difference amount between the overall vector of the two Trombe walls and the horizontal lines. Consequently, what can be argued to be important in the orientation of the buildings is how the Trombe walls are oriented. For the buildings with 75 per cent glazing area, the same scenario can be interpreted for the sides with windows, as the solar energy gained through windows is comparable with the one gained through Trombe walls.

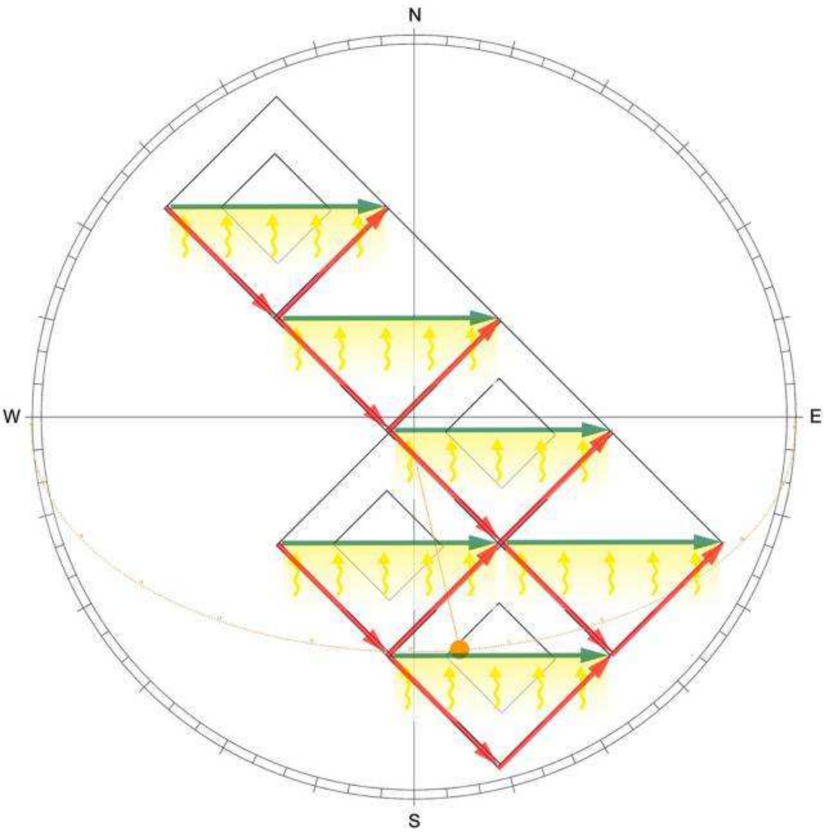

Figure 21.
G3.4_25% posed at its optimised orientation while its overall vector of PSHGEs facing southwards

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6.5 Energy consumption amount

Energy saving percentage has been calculated based on the difference between the overall gained energy of a building at its best orientation to its worst one. Table V represents the results of such comparison. High percentages for cases with 25 per cent glazing and relatively low percentages for cases with 75 per cent glazing accentuate the importance of this parameter for a sustainable building. Energy saving as high as a range of 80 to 105 per cent indicates a huge amount of conservation for buildings with less glazing while, as it can be deduced from Table V, buildings with higher glazing amounts such as 50 and 75 per cent can aim for a save of 46 to 71 and 16 to 43 per cent, respectively. Thus, more importance should be put on a careful determination of a building's orientation.

6.6 Design guidelines

Architectural designers of projects located in regions with the same latitude as Tehran or similar climatic conditions are advised to take the influential factors that are discussed in this study into consideration. These suggestions, unlike the ones in the discussion chapter, are generalised and can be applied to any building in similar climatic conditions.

The determination of a building's optimised orientation strongly depends on several factors. Generally speaking, a rectangular-shaped building is best oriented east-west and sometimes with a slight inclination towards the east. Considering this instance, the building's south-facing windows are regarded as solar windows and therefore its PSHGEs; however, when a building has a variety of PSHGEs in several directions, their overall vectors determine its optimised orientation.

When PSHGEs' properties and location, the R_C, shape and glazing percentage change, it is not as easy to predict the optimised orientation; consequently, designers are given the findings of this study to correctly estimate their buildings' optimised orientation:

- *The impact of the R_C*: This factor applies to buildings with a low amount of glazing percentage. Having considered the mentioned criterion, buildings with the R_C values closer to 0.5 are to face the overall vector of their PSHGEs towards the southeast, and as the amount of the R_C increases, the overall vector of their PSHGEs should face towards the South.
- *The impact of shape*: Variations in shape for buildings with the same R_C does not make any difference in their energy performance which allows architects to create different shapes.

	Group 1				Group 2				Group 3				Group 4			
WWR	G 1.1	G 1.2	G 1.3	G 1.4	G 2.1	G 2.2	G 2.3	G 2.4	G 3.1	G 3.2	G 3.3	G 3.4	G 4.1	G 4.2	G 4.3	G 4.4
25%	97	99	97	97	96	105	88	101	80	98	85	86	81	81	85	80
50%	61	71	68	64	63	67	53	61	47	61	55	54	47	46	46	49
75%	25	24	39	16	38	43	24	21	22	37	23	29	19	16	16	24

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Table V. Energy consumption percentage of cases in their optimised orientation in comparison to their worst orientation

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- *The impact of glazing percentage (WWR)*: Lesser amount of transparency in buildings' facades necessitates buildings to orient the overall vector of their PSGHEs towards the South, and the ones with higher amount of transparency are to be inclined more to the West.

To obtain accurate orientation degrees, it is advised to run simulations with relevant meteorological data.

7. Conclusion

The research suggests that the optimised orientation of the studied buildings in Tehran is between 298 to 318 degrees, and despite what thought to be true, the optimised orientation for a building is not always south to south-east, but it is determined by the PSHGEs of a building. In case, a building has several PSHGEs; their overall vector plays the major role in this matter. In other words, net gained energy reaches its maximum when the model gains maximum solar energy.

The worst degree of orientation for the studied buildings in Tehran, at which net gain is minimum, is between 171 and 177 degrees. The annual energy saving percentage for buildings oriented to their optimised orientation compared to their worst orientation ranges from 16 to 105 per cent from which buildings with lesser amount of glazing save more energy (up to 105 per cent) and the ones with higher amounts can save lesser but still significant energy.

Amongst the studied factors, glazing percentage plays the most important role in determining a building's orientation. The less the amount of glazing, the more a building should be oriented to the south, and the more the amount of glazing, the more it needs to be oriented to the southwest. The R_C has a less important influence and only on buildings with small amount of glazing percentage imposing the overall vector of their PSHGEs to incline towards the east.

Due to the fact that orientation can save up to 105 per cent energy annually, a careful approach towards this parameter is proposed to be taken.

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