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THE EFFECTS OF ROOFLIGHTS ON ENERGY PERFORMANCE OF A COMMERCIAL RETAIL BUILDING IN A SUB-TROPICAL AND A TEMPERATE CLIMATE

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ABSTRACT

The research aims to develop an energy efficient solution by predicting nature of energy use for a retail building with Rooflights in a sub-tropical and a temperate climate of Australia. The research highlighted in the study include (a) the maximum amount of Rooflights area that can make a retail building energy efficient; and (b) the effects on other building elements for the increased use of Rooflights. The study demonstrates that maximum 20% Rooflights of a conditioned space can be applicable for a retail building for an energy efficient solution i.e. improvement of annual energy saving (kWh/yr). To achieve this, building elements such as glazing, insulation, and colour need to be changed.

INTRODUCTION

Buildings worldwide account for a surprisingly high 40% of global energy consumption (Energy Efficiency in Buildings, 2009). Heating, ventilation and air-conditioning (HVAC) consume nearly 33% of total energy consumption of commercial buildings in Australia (CIE, 2007). In addition to heating and cooling energy consumption, lighting consumes the maximum amount of energy, accounting for as much as 40% of electricity costs in well ventilated offices and therefore needs greater attention to improve energy performance and reduce CO_2 emissions (CIBSE, 2004; Brett Martin, 2006). To reduce lighting energy consumption, daylighting is considered as an option. Effective application of daylighting helps to achieve the thermal comfort benefits such as healthier and happier working environment and reduced absenteeism, which result in improved productivity of building occupants (Envo-Care, 2013). Through rooflighting, the distribution of lighting could be even better on larger structures and as much as three times more than the same area covered by vertical glazing (NARM, 2009). All of the above studies discussed about daylighting and not the effects of Rooflights on elements of buildings, cooling and heating. Retail buildings may often require Rooflights to minimise the use of artificial lighting as well as to optimise heating and cooling benefits in day time operation. Heating and cooling energy designs are benefited from the appropriate use of Rooflights for a specific climate. These also lead to reduced energy consumption and reduced CO_2 emissions for the buildings. A case study in UK highlighted that 70% of lighting energy savings and 45% overall CO_2 emissions reductions can be achieved for a industrial building with 12%-15% Rooflights. However, the heating can be optimised less than 40% in this case (Wang et al., 2013). There were several studies on Rooflights application of office building conducted by researchers all over the world in temperate climate regarding the close co-relation between energy saving potentials and daylight options (David and Marcus, 2007; Krarti et al. 2004). A simulation case study on Rooflights in Malaysia pointed out that double polycarbonate layer as Rooflights with change in building elements such as dimension of roof, glazing, reflective materials and building materials can be a solution to maintain indoor comfort for tropical climate (Al-Obaidi et al., 2013). However, none of the above studies co-related the total energy consumption (kWh/yr) including lighting, equipment, heating and cooling of a building with percentage of Rooflights used in retail building. Further, none of the studies demonstrated the maximum amount of Rooflights of conditioned space which can be implemented within the range of Building Code allowances using heating, cooling and overall energy consumption of the retail building. In addition, none of the above studies differentiated the results in Sub-tropical and temperate climate, and verified impacts on other building elements to optimise energy consumption of the retail building. In Australia, commercial retail buildings such as retail stores often use Rooflights to allow natural sunlights not only to optimise use of artificial lighting and to reduce the heating load but also to optimise the cooling load of the building. The Section J verification method of National Construction Code (NCC) of Australia allows to design a building with a condition that the proposed designed building needs to be energy efficient than code compliant Reference Building (JV3, NCC). A Reference building is a code complaint building which uses deemed to satisfy (DTS)-allowance of building materials. These include building insulation, glazing, design conditions and 5% area of Rooflights in a conditioned space. However, any building design can be made of more than 5% Rooflights if its annual energy consumption is less than code compliant Reference Building. So more than 5% Rooflights but less energy consumption is a key criteria to find out the maximum amount of Rooflights that can be applicable to a retail building in Sub-tropical (Climate zone 2) and temperate climate (Climate zone 6) of Australia. To achieve this, impacts on other building elements are investigated in this study

METHODOLOGY AND MODELLING

The methodology adopted in the study was divided into two parts. First, selection of building elements for the proposed building was examined by software simulated results and then investigated to determine the effects of increased Rooflights. Second, simulation of the whole building was carried out in both stages. Australian Building Code Board (ABCB) approved software DesignBuilder and IES were used in this study (ABCB protocol, 2006).

Selection of building elements for base case

The whole methodology for finding the energy efficient and cost effective options is shown in Figure 1. First, all architectural design data including floor plan, elevations, sections, site plan, wall and roof constructions, glazing and finishes schedules were collected.

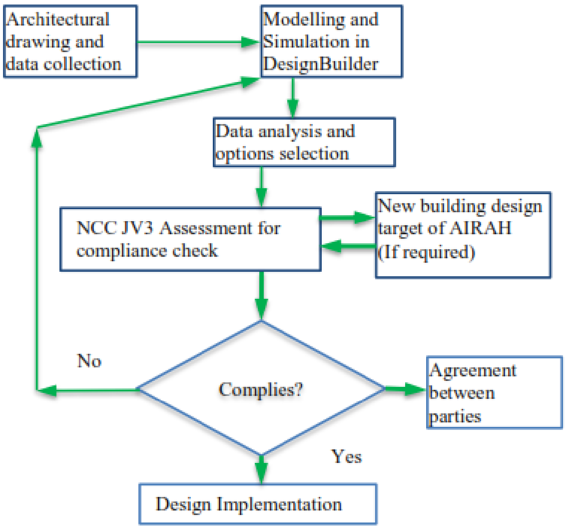

Figure 1: Building elements selection process

Second, DesignBuilder version 3.4 software along with EnergyPlus version 8.1 simulation engine was used in this study to investigate the energy performance for the proposed building. Using all the information and architectural drawing, a model building was developed in DesignBuilder. The 3D view of the model building with Rooflights and floor plan are shown in Figure 2 and Figure 3. A brief description of the modelled Retail building is given in Table 1. Deemed to satisfy (DTS) Lighting and HVAC schedules for JV3 (Office schedules: 2500 hr/yr) as per NCC were used in the simulation to satisfy the section J performance requirement (JP1). After the modelling, the construction details and glazing were inserted in DesignBuilder thermal simulation. Third, the energy simulation for Annual Energy Consumption of the proposed building was conducted using different colour options of external walls and roof, without changing the insulation requirement of the external walls and roof. After that, walls and roof insulation were changed in building model and simulated. Then the results were analysed using the DesignBuilder simulation.

Table 1 A brief details of model building

Element	Details
Conditioned Area	Retail Floor area (7100 m^2) with no ceiling, Office (200 m^2) and Cafe (220 m^2) with ceiling; Facade Height: 7m-8m
Unconditioned Area	Garden (Open in most areas) and Trade Area (Enclosed with Rooflights)
External walls	External :Metal Insulated panel
Walls: Internal partitions	Insulated panel wall between Retail and Trade Area; Cavity panel to other partitions
Plaster Ceiling	Height: 2.7 m to Office/Cafe
Ground Floor	Tiles with Concrete slab
Glazing	6 mm Generic clear glass
Metal Roof	3^0 pitch, Bulk insulation and foil

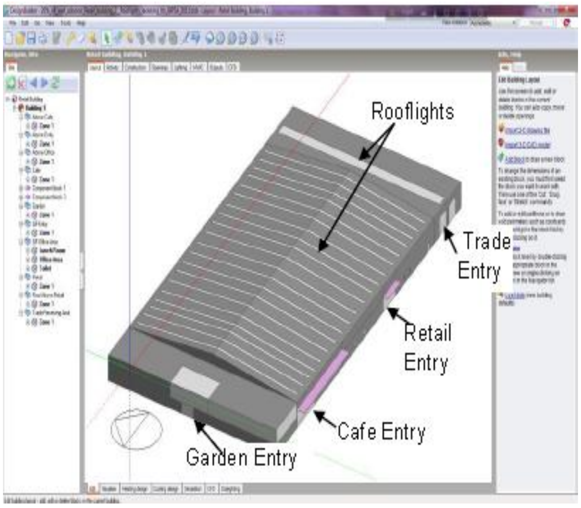

Figure 2: A 3D model building in DesignBuilder

When the requirement of wall and roof insulation was fixed, then the simulation was carried out using different glass products with different U value and Solar Heat Gain Coefficient (SHGC). A Reference building was modelled as per deemed to satisfy

(DTS) building elements based on constructions of walls, roofs and ceiling.

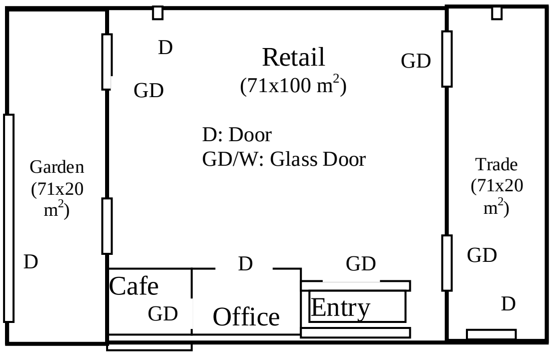

Figure 3: Floor plan of the proposed building

NCC lighting calculator (NCC lighting, ABCB) and Glazing calculator (NCC Glazing, ABCB) were used for Reference Building. Then JV3 conditions of NCC were applied to the reference building as per Table 2. The Annual Energy Consumption between the proposed and reference building was compared and decision was made when the proposed building's energy consumption was less than Reference Building. Finally, Table 3 was developed for the proposed building for the base case as the following combination complies with NCC as per JV3 method.

Table 2 JV3 Criteria and Reference Building details

JV3 Assessment Criteria
a. 3D model of the building with location and orientation; Schedules for: occupancy, internal heat loads, lighting and HVAC system **;** Simulation hours: 8760 hours, at least 2500 hours/year; Thermostats setting: 18°C to 26°C;
b. Air conditioning and Artificial Lighting complies: NCC Parts J5 and J6; The air conditioning & heating Annual Energy Efficiency Ratio (AEER): NCC Performance Requirement JP3, Cooling AEER: Minimum Energy Performance Standards (MEPS); HVAC Design Factors: 1.0 for 98% coverage; Fresh air rate: 10L/sec/person. Infiltration: 1.0 air changes/hour
Reference Buildings Construction Details
c. Solar Absorptance (α): Walls = 0.6; Roof = 0.7; Deemed to Satisfy (DTS) compliant insulation in all envelope elements; DTS-compliant lighting and glazing to all orientations including roof lights

Rooflights application on modelled building

For simplicity in calculation, the Rooflights dimension was (35m x 1 m) in the proposed building model. Practically width of Rooflights sheet vary from 760 mm to 800 mm. The Rooflights were placed uniformly on roof with even number of gaps. The number of Rooflights was determined based on total area of each sheet and conditioned space area. To check the suitability of Rooflights for a NCC-compliant building solution, a range of U value and SHGC of Rooflights was selected and being inserted in the model. The Table 4 was used for thermal simulation.

Table 3 NCC Compliant optimised building elements

Element	**R value of Construction**
External walls	Insulated panel R2.8 (~100 mm)
Internal walls	Insulated panel R2.8 (~100 mm)
Ceiling	Plasterboard to Office areas
Floor ground	Tiles to 200 mm Concrete slab
Glazing	U =5.8 (W/m^{2}K) SHGC 0.82
Metal Roof	R2.5 insulation with foil-backed

Table 4 Type of Rooflights used in thermal simulation

Type	**Colour**	**U(W/ m^{2}K)**	**SHGC**	**VT**
Single layer (SL)	Light	5.8	0.23	0.38
Multilayer (ML)	Light	1.4	0.18	0.30
SL	Ice	5.8	0.74	0.64
SL1	Opal	5.8	0.72	0.68
SL2	Opal	5.8	0.45	0.45
SL3	Diffuse Ice	5.8	0.18	0.20

First, 5% Rooflights of the conditioned space (7100 m^2) were applied to the modelled building. The Rooflights' U value 5.8 Al frame, SHGC 0.23 and visible transmission (VT) 0.38 were set for the proposed building model. A Reference building was modelled with 5% Rooflights following the specification of DTS compliant value for the JV3 specification. As Reference building only allows 5% Rooflights, so the total annual energy consumption number represents the benchmark value for NCC compliance.

Subsequently, the increment of Rooflights in the proposed building model was increased by 5% to see the variation of heating, cooling and total annual energy consumption number. However, before increment of Rooflights in the proposed building model, a similar model building was developed in IES software with JV3 assessment criteria and ASHRAE thermostat setting which includes 21^0 for heating and 24^0 for cooling (ASHRAE, 2009). The purpose was to check the monthly heating, cooling and total annual energy number (kWh/yr) variations with DesignBuilder thermal simulation. A 3D model of the building with Rooflights in IES is demonstrated in Figure 4.

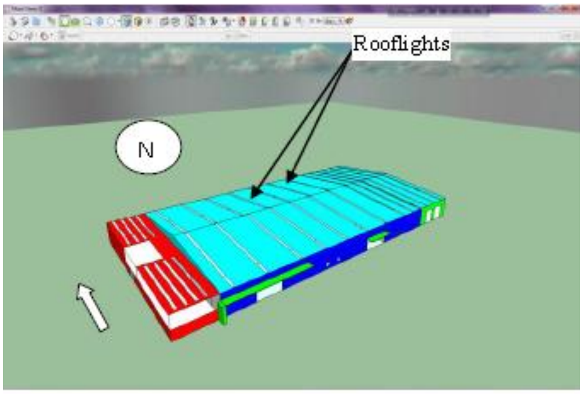

Figure 4: A 3D model building in IES

The second simulation in the IES also optimised error for the software defaults number in calculation. Once the results demonstrated the close monthly and annual energy numbers, the Rooflights in the proposed building model were changed. The simulations were conducted for 10%, 15% and 20% Rooflights starting from 5%. In simulations, when the total energy number was less than Reference building's energy number, it demonstrated an energy efficient and compliant building solution.

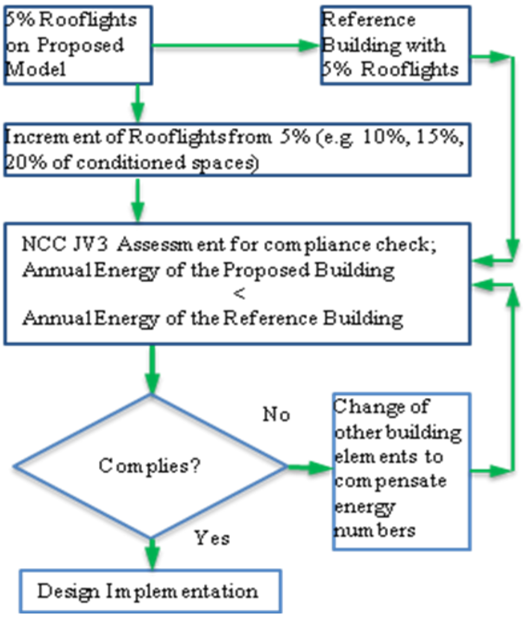

Figure 5: Flow chart for investigation of Rooflights

If the annual energy number exceeded the Reference building's energy number, it was non-compliance with NCC. Other building elements such as insulation, glazing and building colour were examined for improvement of annual energy consumption. Then numbers of re-simulation were conducted for the proposed model with variations of values such as R-value of insulation or glazing SHGC or solar absorptance of walls and roofs. Finally, the solutions of the proposed building were established for increased Rooflights. The above procedure was followed for both Sub-tropical and temperate climate of Australia. For Sub-tropical climate, weather data for Brisbane (27^0 S 153^0 E) and for temperate climate, weather data for Melbourne (37^0 S, 144^0 E) were used in DesignBuilder and in IES software. A flow chart for Rooflights applications is shown in Figure 5.

SIMULATION RESULTS ANALYSIS

A Sample result from the DesignBuilder thermal simulation is shown for the proposed building model in Table 5. The numbers represent the cumulative energy transfer totals relative to conditioned spaces. Positive numbers indicate energy transfers from outside to inside of the building and negative means the vice versa for a building component. Room electricity and lighting remain same for all thermal simulations. All of the building components including walls, roof, ceiling, partitions and glazing influence the thermal simulation results. Glass doors, windows and Rooflights provide the two energy transfer elements. One of them is conduction energy transfer. It is included in Glazing under fabric and ventilation row of Table 5. The second one is solar heat gain by exterior windows under internal gains row. Exterior windows include glass doors, windows and Rooflights. Once the modelled building was simulated in DesignBuilder under JV3 conditions, the same model building was simulated under ASHRAE conditions with different thermostat setting. After that, the same model building is developed in IES with ASHRAE conditions and then simulated. From Figure 6, it was demonstrated that monthly energy numbers were almost similar or 2%-10% varied in some months. Over all, the total annual energy numbers had a variation of 1%-2%. Starting from the base case, only Rooflights were changed on a percentage basis, and all other building elements were kept same to obtain a NCC-compliant solution. However, if the complaint solution was not obtained for the increment of Rooflights, then other building elements were changed.

To eliminate errors and to avoid wrong results, the building model and simulation results were cross checked in IES. Once the two software results were identical, the next stage was to investigate the energy performance of the proposed building with increased Rooflights. The next two sub-sections highlighted the effect of Rooflights in two different climates of Australia. First, the results of sub-tropical climate and later the results in temperate climate were analysed and discussed.

Table 5 A sample result of building simulation

Electricity Breakdown	**kWh/yr**
Room Electricity	221853
Lighting	558011
Heating (Electricity)	17850
Cooling (Electricity)	166263
Fabric and Ventilation	
Glazing	-124592
Walls	23416
Ceilings (int)	-10676
Floors (int)	10581
Ground Floors	-1415650
Partitions (int)	-5
Roofs	126595
External Infiltration	-352241
External Vent.	-59030
Internal Gains	
General Lighting	558011
Computer + Equip	221853
Occupancy	230759
Solar Gains Interior Windows	890
Solar Gains Exterior Windows	936340
Zone Sensible Heating	40699
Zone Sensible Cooling	-346647
Sensible Cooling	-346575
Total Cooling	-515416
Zone Heating	40699
Total Energy (kWh/yr)	**963977**

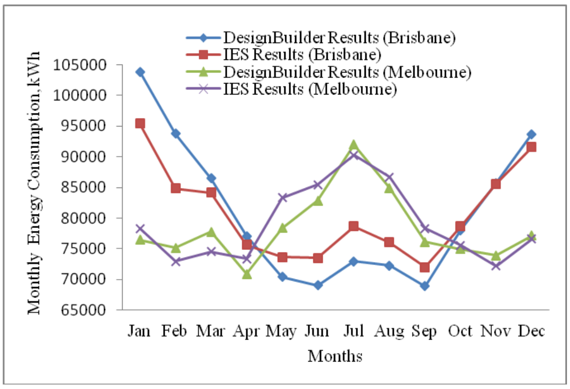

Figure 6: Monthly Energy Consumption (kWh) in DesignBuilder and IES

Sub-tropical Climate

In Sub-tropical climate, monthly energy numbers were lower in winter months (June, July and August) compared to other months. Only heating is required in these months rather than cooling, so the energy numbers dropped significantly compared to other months of the year. Heating requirement was 10 to 12 times less than the cooling requirement as shown in Figure 7 for number of cases. So, the cooling energy numbers have a significant impact on total annual energy numbers.

After the number of simulations conducted in DesignBuilder, the Table 6 was developed as a compliant solution based on increased roof lights, using the procedure described in methodology section. First 5% Rooflights were applied in conditioned retail space, then Rooflights were applied in unconditioned trade area.

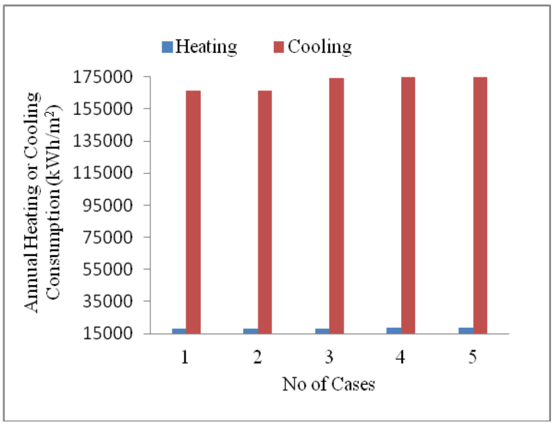

Figure 7: Annual Heating and Cooling Energy consumption

Second, Rooflights' percentage was increased in conditioned area of retail. From the base case, the number of simulations was conducted in DesignBuilder for different combinations of building elements. The results presented in the Table 6 are five solutions for the proposed building model. It was examined that Rooflights in unconditioned space had almost no effect on total energy consumption of the building as shown in case 1 and case 2 in Figure 8.

Table 6 Increment of Rooflights and effect on other building elements

Case	**Rooflights to conditioned (C) /unconditioned (U)**	**Other elements from optimised base case**
1	5% (C)	External walls: R2.8 Internal walls: R2.8 Ceiling: Plasterboard Ground Floor: Tiles to 200 mm Concrete Glazing: U 5.8 (W/m^{2}K) SHGC 0.82, Al frame Roof: R2.5 Rooflights: U5.8 (W/m^{2}K) SHGC 0.23
2	10% (U)	
3	10% (C)	
4	15% (C)	
5	20% (C)	

The building element combinations presented in Table 6 demonstrated that upto 20 % Rooflights are acceptable in Sub-tropical climate, if single layer light coloured rooflight (Ug 5.8 SHGC 0.23) was used for this type of modelled building. There was no need of changing building elements from the base case. However, to optimise the construction cost of building materials, it was necessary to check alternative solutions for the building elements.

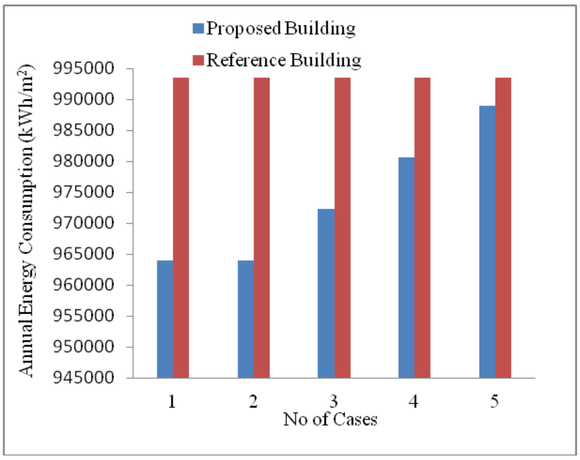

Figure 8: Annual Energy numbers for the five solutions

The Figure 8 illustrated that the annual energy number difference between proposed and NCC-compliant Reference building was 0.5% to 3%. Hence, there were still chances of optimising other building elements to reduce the construction cost. To do this, further simulations were done in DesignBuilder for indentifying building materials that can be changed so that minimum effect on annual energy numbers can be obtained as depicted in Figure 9. The difference between two options was nearly 0.5% for annual energy numbers.

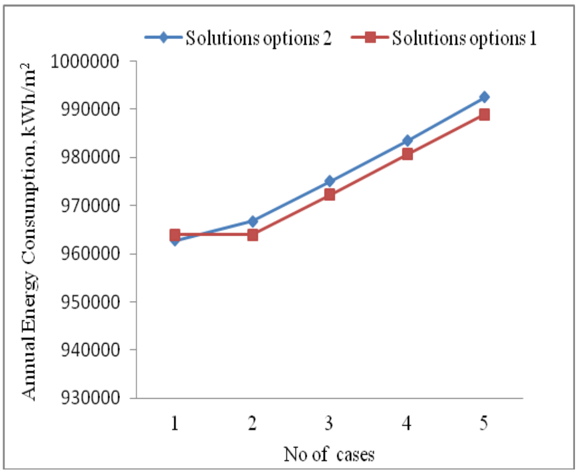

Figure 9: Annual Energy numbers for the cases

Finally, the results in the Table 7 showed that R1.5 insulation instead of R2.8 insulation in external walls can be used. This allows 15% Rooflights for the proposed retail space. For 20% Rooflights in the conditioned space, a reduction of insulation from R2.8 to R2.0 can be an optimised and compliant building solution as presented in Table 7. However, if the wall insulations were not changed, the change of clear glass or increment of shade was another alternative solution for 5% Rooflights.

Table 7 Second Optimised solutions for building elements

Cases in Solutions options 2	Change of elements : Glazing / External walls
1	5% Rooflights with Low e clear glass (Ug 3.6 SHGC 0.68) or increment of shade
2	5% Rooflights with R1.5 insulation
3	10% Rooflights with R1.5 insulation
4	15% Rooflights with R1.5 insulation
5	20% Rooflights with R2.0 insulation

Temperate Climate

In temperate climate, heating requirement was more dominant than cooling requirement as total energy numbers were higher in winter months than other months of the year as shown in Figure 10 for number of cases. The annual heating numbers are 2 to 3 times more than annual cooling energy numbers.

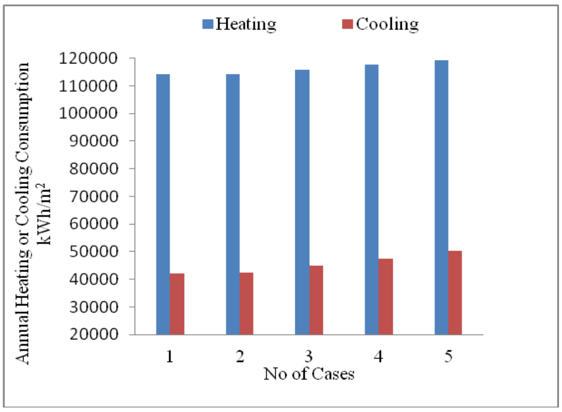

Figure 10: Annual Heating and Cooling Energy consumption

Following the procedure described in the methodology section, it was confirmed that increment of Rooflights from the optimised base case in temperate climate didn’t achieve compliant building solution for the number of cases (Table 8) as shown in Figure 11. Three out of five cases including 10%-20% roolfights (Ug 5.8, SHGC 0.23) failed to obtain a compliant solution as the total annual energy numbers for the proposed cases (AENp) were higher than AEN of Reference buildings (AENr). The change of other building elements was considered for the modelled building to increase the Rooflights from 5%. The Table 9 showed the number of building elements that were changed to achieve an energy efficient and NCC-compliant building solution in case of increased Rooflights. Starting from the wall insulation change, the changes were also required for the insulation of the internal walls between cafe and Garden.

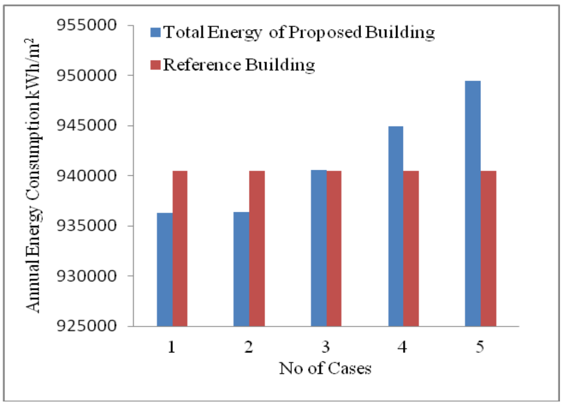

Figure 11: Annual Energy numbers for the five cases

Table 8 Increment of Rooflights from 5% of optimised base case

No	**Rooflights to space**	**(AENp < AENr)**
1	5% conditioned (C)	Compliant
2	10% unconditioned	Compliant
3	10% (C)	Non-Compliant
4	15% (C)	Non-Compliant
5	20% (C)	Non-Compliant

The glazing was changed from clear glass to Low e clear glass with less SHGC. Five solutions were obtained from different combinations of building elements to reduce the construction cost. In case 1, insulation of external walls of east and west side of retail was increased from R2.8 to R5.1. Then, additional R1.0 insulation was added to west wall of cafe. Glazing was also changed to low e clear in that case. Only for cases 2, 3 and 5, multilayer Rooflights were applicable without changing other building elements to the proposed building. However, instead of using multilayer, single layer Rooflights can be applicable with change of insulation to walls, internal walls of cafe and increased insulation to roof as shown in case 4 of Table 9. To apply the maximum 20% Rooflights for the proposed retail building with single layer Rooflights, a range of changes of elements were necessary as shown in case 6 of Table 9. The annual energy numbers for the five solutions compared to Reference building were demonstrated in Figure 12. The Maximum difference between proposed and Reference building was 0.81% and the minimum was 0.01%. In case of 20% Rooflights, it is better to use multilayer Rooflights without changing other building elements to reduce the energy consumption of the building. Depending on the application of the building elements, the annual energy consumption can be saved up to 6000 kWh in temperate climate of Australia.

Table 9 Six solutions for 10%-20% Rooflights

No	**Change of building elements from optimised base case**
1	10% Rooflights (Single layer); R5.1 insulation East and West walls ; R1.0 to west wall of Cafe; Glazing: Low e clear (Ug 3.6 SHGC 0.68)
2	10% Rooflights with Multilayer Rooflights (Ug 1.4, SHGC 0.18)
3	15% Rooflights with Multilayer Rooflights (Ug 1.4, SHGC 0.18)
4	15% Rooflights (Single layer); R5.1 insulation to East and West walls R1.0 to west wall of Cafe; R3.4 insulation to roof
5	20% Rooflights with Multilayer Rooflights (Ug 1.4, SHGC 0.18)
6	20% Rooflights (Single layer); Wall and roof colour: very light : 0.3; R5.1 insulation to all external walls; R1.0 to west wall of Cafe; R4.0 insulation to roof Glazing: Low e Neutral (Ug 3.6 SHGC 0.51). Reduction of glazing in the cafe area: at least 1 m from ground

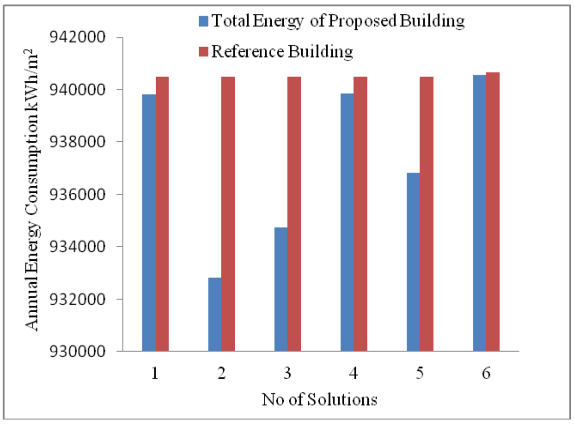

Figure 12: Six solutions for the 10%-20% Rooflights

CONCLUSION

In Sub-tropical climate of Australia, Retail buildings with single layer Rooflights and lower SHGC allow the maximum 20% of Rooflights. In temperate climate, to achieve 20% Rooflights, multilayer Rooflights with lower SHGC are required. The optimised building elements can be further optimised after the application of the Rooflights for sub-tropical climate, whereas lots of changes in optimised building elements are definitely required for tropical climate. The insulation of external walls and roof, SHGC of glazing and Rooflights have significant impact on annual energy numbers for the retail building. In this study, the Rooflights were chosen based on their effect on annual energy numbers, colour, visible light transmission, cost, decision from authorities of the building during the design and development phase for the long-term benefits of energy saving. So, the trade-in elements, i.e. increment and decrement for other building elements are required for a selected type of Rooflights. The key part of the environmental sustainable design phase for the retail building with Rooflights is to focus on the targeted annual energy numbers i.e. heating, cooling and total energy numbers, so that, the amount of energy can be saved annually. In this study, the lighting annual energy numbers were kept constant for all buildings. However, if the maximum 20% of the Rooflights are applied to this type of retail building, the proposed artificial lighting (558,011kWh) used in the analysis can be reduced to at least 40% from the optimised base case. Overheating or requirement of more cooling than usual case can be a problem for Rooflights in a building. Overall, it can be concluded that 20% of Rooflights of the conditioned space of a retail area is the maximum amount of Rooflights that complies with National Construction Code of Australia. Countries have different constructions code for buildings. However, any countries can follow the proposed methodology of optimisation for building elements and Rooflights with a close observation of building code to set the maximum amount of Rooflights for Retail or other commercial buildings. The proposed building model, Rooflights application and optimised elements can be applicable for tropical, sub-tropical and temperate climate in different parts of the world. Researchers can further investigate the proposed building model with percentage of Rooflights for common brand or franchised retail outlet in any climate zones of the world.

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