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Window to wall ratio and orientation effects on thermal performance of residential building: A case of Butwal Sub-Metropolis

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Abstract

The orientation and glazed surface area used for windows in a building have significant effects on its indoor thermal comfort and overall energy consumption. The increasing use of glazed windows and lack of consideration of orientation in building design have become a major problem in warm and humid regions as windows cover sensitive skin areas for the exchange of energy leading to increased solar gain inside the building. This paper describes the effect of the varied 'area ratio of glazed window to the wall for different building orientations' on the thermal performance of the residential building in a warm humid climatic region of Nepal. A typical residential building located in Kalikanagr of Butwal, the fast-urbanizing sub-metropolis of Western Nepal, was selected for the study from 18 houses surveyed using the purposive sampling method. Nine varying values of Window to Wall Ratio (WWR) of glazed façade ranging from 0.1 to 0.9 with a constant increment of 0.1 in north and south façades, and the change in the building orientations were considered for the detailed study. Altogether eighty different test scenarios including base case scenarios were created and annual thermal energy consumption was computed for each test scenario using the Autodesk Ecotect Analysis, 2011. Findings from the study showed that the south orientation is the most appropriate compared to the north-east for all WWR to reduce the building energy consumption and an increase in WWR also results in increased energy consumption. The study concludes the careful considerations of WWR and the south orientation during the designing of building will contribute to efficient energy consumption in residential buildings.

Keywords: *Building orientation; energy consumption; residential building; thermal comfort; window to wall ratio.*

1. Introduction

Buildings and operations, the largest energy-consuming sector in the world, account for the highest share of both global final energy consumption (36%) and energy-related CO_2 emission (39%) (IEA, 2019). In Nepal too, total energy consumption in the year 2008/09 was about 9.3 million tonnes of oil equivalent (401 million GJ). The share of residential energy accounts for nearly 87% of the total final energy consumption in Nepal

(WECS, 2014). There are growing global and local concerns to reduce the energy consumption and resulting carbon footprint and efforts are being made to develop and deploy sustainable construction technologies, systems, and materials in new and existing buildings to meet the sustainable development goals. As a part of sustainable construction technology, Butera (2005) has highlighted the importance of window glazing as an important technological innovation to achieve indoor thermal comfort[1] in enclosed spaces since after the Renaissance period. According to him, it provides a noticeable thermal comfort improvement in the indoor space since glass is capable of trapping solar radiation in the room, and in the winter sunny days, indoor thermal comfort is improved even without a source of heat. This, however, requires a good balance while combining the opaque and transparent elements of the building envelope to achieve the desired daylight, thermal performance, and the building's energy efficiency. Chi et al. (2020) call it a technique (or passive strategy) that aims at controlling and regulating the infiltrated solar radiation and ventilation to create a healthy indoor environment. The good balance, in this sense, is dependent on the Window-to-Wall Ratio (WWR), which is defined in terms of window size expressed as glass ratio of a building façade (Hassan, 2016) and the Building Orientation (BO) that affects sun exposure and resulting thermal acquisition, ventilation, and lighting (Elghamry and Azmy 2017).

Several researchers have examined the relationship between the various dimensions of WWR including the use of glazing, shading, and orientation and their effects on the thermal performance of the building. Ghosh and Neogi (2018) in a simulated result on the effect of fenestration's geometric factors on building energy consumption in a warm and humid climate showed that the increase in WWR in south-facing air-conditioned building cell[2]; heating, and lighting energy consumption decreased whereas the cooling energy consumption increased. Similarly, eighteen building orientation intervals and eight WWR interval combinations were analyzed using Ecotect 2016 and PHOENICS 2012 simulation software by Chi et al. (2020). The analysis revealed that the best WWRs for N-W 80 and S-E 80 are 0.39 and 0.4 respectively. According to the research performed by Nair et al. (2014) using Design Builder and Energy Plus simulation software, the South orientation and 15% WWR showed the best effect in the case of the composite climate of Rajasthan. Likewise, comparative experimental and simulation studies for thermal performance analysis in residential buildings in Hot-Humid climate conducted by Al-Tamimi and Syed Fadzilb (2010) showed that rooms with high WWR are relatively cool during night time only whereas low WWR performs well results during daytime and night-time. Nearly Zero Energy Building's most energy-saving WWR design scheme in severe cold areas is that the east WWR ranges from 10% to 15%, the south WWR from 10% to 22.5%, and decrease the north WWR decreases appropriately if the conditions of light and ventilation allow it (Feng et al. 2017). Although energy consumption has been strongly influenced by climatic conditions, structural insulation characteristics, façade configurations, presence of shading devices, the optimal WWR does not seem to vary significantly if the effect of each factor is evaluated individually (Marino et al. 2017).

In Nepal, which has a very diverse topography with varying climatic zones, the building design process requires a good understanding of the effects of WWR and BO on the thermal performance of the buildings as the use of glazed windows and their size are sensitive to solar gain and indoor heating. Although several studies were carried out to examine the effect of WWR and BO on the thermal performance of public buildings, not much information is available on such effects in case of residential building types. In this context, this paper aims to analyze the climatic data, find out the best orientation and examine the effect of the WWR and BO on the thermal energy consumption of the residential building in the warm and humid climatic zone mostly prevailing in eastern parts of the Terai (plains) of Nepal. The understanding of the effect of WWR and BO in the thermal energy consumption is expected to have significant practical

1 *ASHRE (2010) defines thermal comfort as the "mental state which expresses satisfaction with the thermal environment"*

2 *The air-conditioned building cell of dimension 5m x 5m x 3m was simulated in Energy Plus simulation software by Ghosh and Neogi (2018)*

implications in achieving better thermal comfort and reduce the running cost of the active system in new construction and retrofitting of the existing buildings. It will help, among others, the design practitioners and policy planners in making design and planning decisions.

2. Study Methods

The quantitative methodology was used for the study. A household survey of 18 houses was carried out in Kalianagar of Ward no 10 of Butwal sub-metropolis based on the residential categories, Sub Group A1[3] (NBC:206, 2015). The houses were selected using the purposive sampling method based on the researcher's knowledge and experience. A structured questionnaire survey was carried out to get the general idea of the thermal sensation as experienced by the occupants. Out of eighteen surveyed houses, a typical building (latitude 27° 40' North and longitude 83° 27' East) representing the general modern residential building typology of Butwal was then selected for the simulation purpose (Fig. 1). "Autodesk Ecotect Analysis, 2011" simulation software[4] was used to analyze the selected typical building to evaluate the effect of WRR and BO on energy consumption.

The methodological process further involved the analysis of weather data[5] of 10 years (2007-17) obtained from the Department of Hydrology and Meteorology (DHM). The weather file was then edited and created in "WEA" format as input data for Autodesk Ecotect Analysis, 2011. The Ecotect simulation software in which the thermal performance analysis is based on the admittance method as laid out in the CIBSE guide A (CIBSE, 1999), was adopted for its users' friendliness. The different thermal and non-thermal zones were created using field data. The comfort band, calculated by neutrality temperature for the case study area, is then assigned and the selected building was simulated in the mixed-mode in all thermal zones. Input data related to occupant's activities and building uses were taken from field and the thermal properties of materials from the inbuilt data made available by simulation software itself. The building was modeled and as many as 80 simulated scenarios were developed and interpreted based on the different WWR and orientation to evaluate their effects on thermal performance.

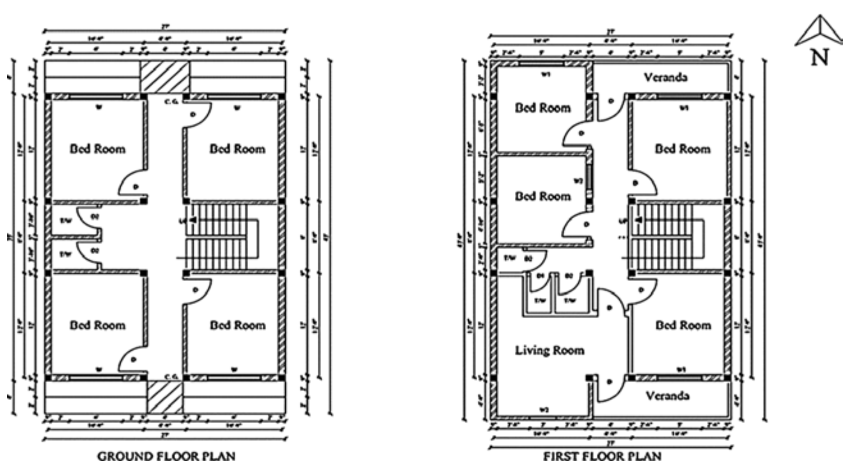

Figure 1: Plan views of the selected typical building.

3 The Sub Group A1in NBC code is defined as general residence which includes any private residential building having sleeping accommodation for up to 40 people and a built up area of not less than 500 square meter

4 *Autodesk Ecotect Analysis, 2011" simulation software is widely used to analyse the thermal and energy performance of the building (Al-Tamimi and Syed Fadzilb 2010).*

5 *Data related to dry bulb temperature, relative humidity, rainfall were collected from Department of Hydrology and Meteorology (DHM). Additional unavailable data like wind speed, wind direction, solar radiations were collected from NASA website. The data from both sources were compared to fill the data gap and finally temperature and relative humidity were used from DHM and solar radiation data from NASA website to construct the building bioclimatic chart*

3. Results and Discussion

The analysis of weather data obtained from DHM revealed that the warmest month is April with a maximum air temperature of 37.03 °C while the coldest month is January with a minimum air temperature of 10.66 °C. Although the relative humidity is high throughout the year; July, August, and September witness higher relative humidity due to the monsoon (Fig. 2). The weather data analysis confirms that the Butwal sub metropolis has a warm and humid climate.

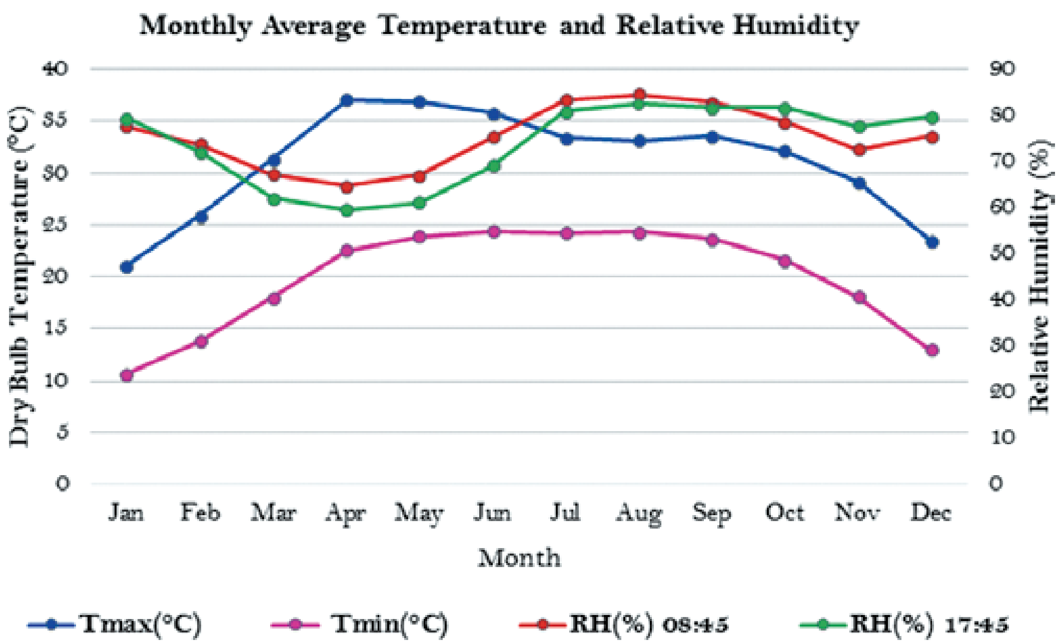

Figure 2: Average monthly air temperature and relative humidity.

The climate data including dry bulb temperature, relative humidity, rainfall, solar radiation, wind speed, and directions were edited to create a weather file in ". WEA" for the purpose of weather simulation. The simulated weather data revealed the best and worst orientations. It showed that the best orientation is 187.5° clockwise from the north and the worse orientation is 97.5° clockwise from the north (Fig. 3).

The survey result of the case area showed that more than 77% of the total houses surveyed were found to be modern type which is defined as a permanent building having an RCC frame structure. Likewise, the south and north-oriented housing accounted for 28.0 % each. Respondents living in traditional and modern houses surveyed stated that they needed room cooling from April to October whereas the majority of respondents living in modern houses reported that they required room heating in the winter season. A twelve-month electricity unit consumption of the surveyed buildings showed the increment in electricity unit consumption due to the cooling load from the month of March to September with a peak in the month of June. As for the residential indoor thermal satisfaction, the majority of the people living in modern buildings were found to be satisfied despite the inferior thermal comforts in their homes.

A typical building (Fig. 4) selected, for the analysis based on the survey result is a three-story, north-oriented with a floor height of 3.35m. The top floor is unoccupied and covered with Corrugated Galvanized Iron (CGI) roofing. The ground floor has timber window frames and timber paneled shutters whereas the first floor has single glazed timber frame windows. Both windows are operable towards the outside in the north and south-facing walls. The existing building (base-case) was modeled in ECOTECT simulation software to create sixteen thermal zones (Fig. 5) in such a way that each room on the ground and first floors (Fig. 1) was a zone. The verandas on the first and top floors were considered non-thermal zones as they are not enclosed spaces.

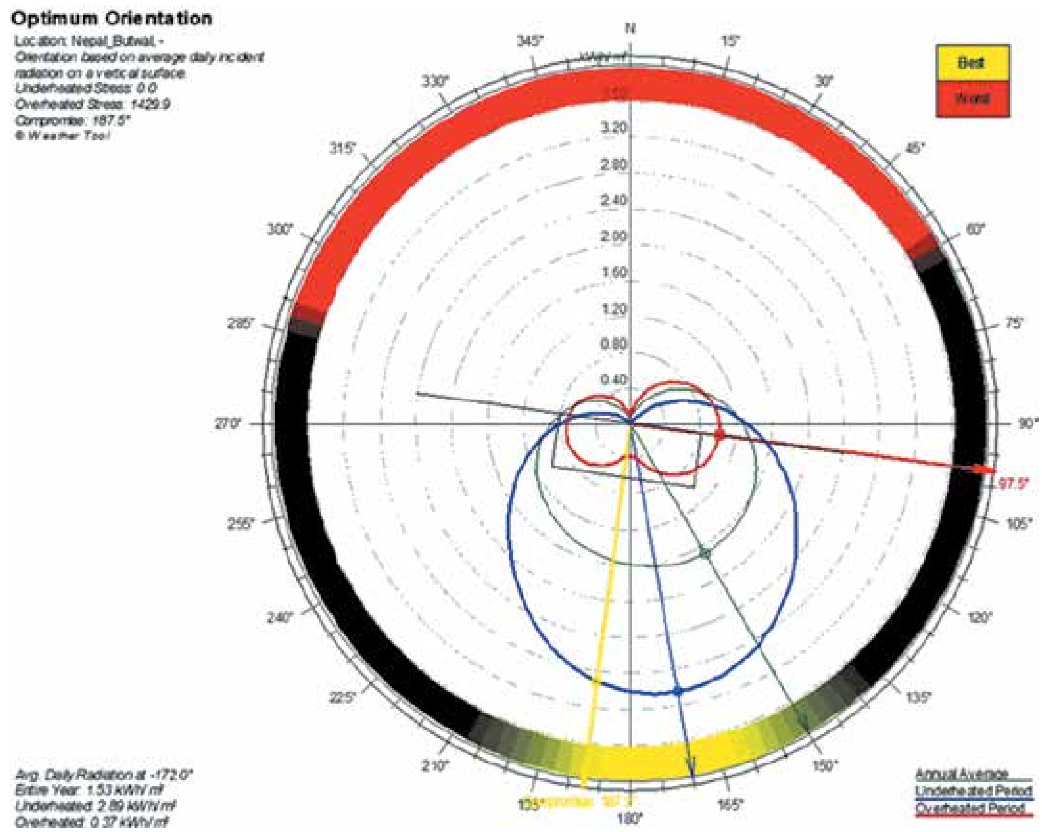

Figure 3: Best and worst orientation in the study area.

The comfort band, calculated by neutrality temperature[6] for the case study area, was assigned as 22.5 °C to 27.0 °C for a mixed-mode system[7] in all thermal zones. Since none of the residential buildings surveyed used air-conditioning except fans for cooling, the mixed-mode system was chosen as the study intended to compute energy consumption for different case scenarios which otherwise could not be derived by assigning natural ventilation system that gives discomfort hours only. For all zones, the comfort humidity was set as 50% and airspeed as 0.5 m/s for pleasant breeze. Similarly, the air change rate was set at 0.5 ACH for well-sealed condition, and clothing as 0.6 clo.

For the base case, the analysis showed that the existing WWR as 0.35 for the ground floor in the north and south-facing wall; 0.27 for north and south-facing first-floor bedrooms; and 0.15 for the south-facing first-floor living room. The data relating to energy consumption patterns, functional activities, and uses were taken from field data (Table 1) and for thermal properties of the materials inbuilt data from the simulation software itself (Table 2).

6 *The neutrality temperature was calculated using the formula "Tn equals to 17.6 + 0.31x Tav" where "Tn equals to 17.6 + 0.31x 15.86 = 22.5 °C" for coldest month and "Tn equals to 17.6 + 0.31x 30.41 = 27.0 °C" for warmest months.*

7 *The mixed-mode system is a combination of air-conditioning and natural ventilation, where the HVAC system shuts down whenever external conditions are within the specified thermostat*

Figure 4: Two storied building simulated.

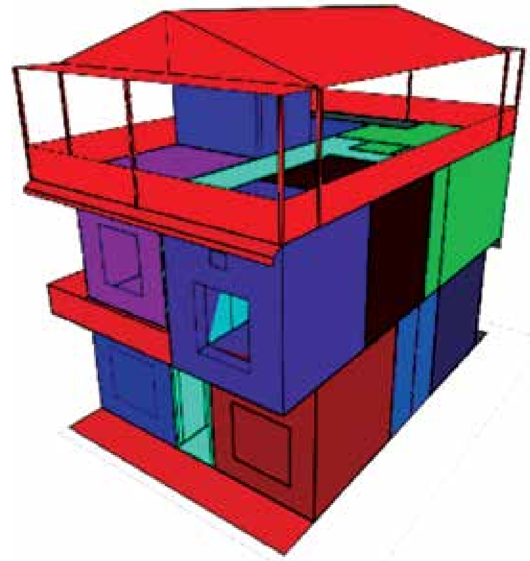

Figure 5: Thermal zones of simulated building.

Table 1: Field data and zone setting.

Zone	Lighting level (Lux)	Zone type	Occupants	Operation schedule
Ground bedroom 1	400	Thermal	2	0-24
Ground bedroom 2	400	Thermal	0	18-19
Ground bedroom 3	400	Thermal	2	0-24
Ground bedroom 4	400	Thermal	1	0-24
Ground restroom	200	Thermal	1	7-8
Corridor	200	Thermal	0	-
First-floor living kitchen	400	Thermal	3	8-10
First-floor bedroom 1	400	Thermal	0	22-6
First-floor bedroom 2	400	Thermal	2	22-6
First-floor bedroom 3	400	Thermal	1	22-6
First-floor bedroom 4	400	Thermal	3	10-18
First-floor restroom	200	Thermal	1	6-7
First-floor front balcony	200	Non-thermal	0	-
First floor back balcony	200	Non-thermal	0	-
Staircase	100	Thermal	0	-
Top floor	50	Non-thermal	0	-

Table 2: Thermal properties of building materials.

Components	Materials	Thickness (mm)	U-Value (W/m2k)
Roof	CGI	2.6	5.62
Wall	Brick Plaster	130	2.8
		250	1.9
Door	Door core timber	30	3.11
Ceiling	RCC with plaster	125	3.25
Floor	Stone soling PCC	260	2.78
Timber frame	Timber pane	30	3.11
Windows	Single glazed	6	5.44

In test scenarios created, the existing WWR and the orientation were changed from the base-case scenario. Considering the different building orientations and combinations of WWR and two evaluation parameters of heating and cooling energy consumption for each case, a total of 80 test scenarios were proposed for investigation.

Firstly, a total of eight test case scenarios including base-case were evaluated by rotating building (base-case) in eight different orientations i.e., North (N), North-East (NE), East (E), South-East (SE), South (S), South-West (SW), West (W) and North-West (NW) for existing WWR and resulting heating and cooling energy consumption were obtained. The result showed that annual thermal energy consumption (Fig. 6) decreased by 0.24% for the south orientation and increased by 1.31% for the north-east orientation as compared to the existing north orientation.

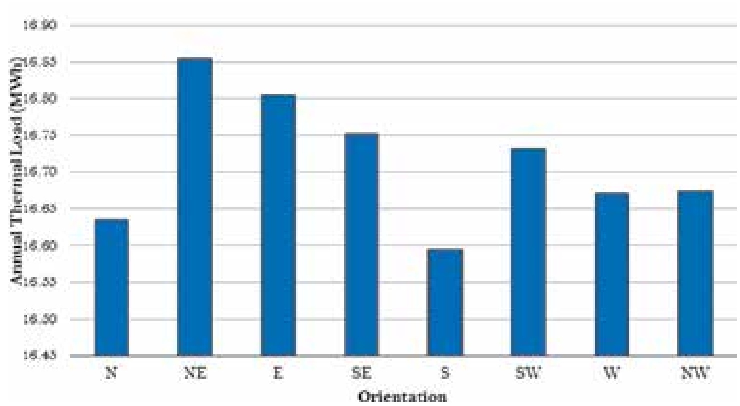

Figure 6: Annual energy consumption for existing WWR.

Secondly, a constant increment of WWR by 0.1 from 0.1 to 0.9 in eight different building orientations was simulated and 72 test scenarios were compared. For example, WWR was set as 0.1 for all glazed windows on the first floor keeping the timber panel window on the ground floor intact. The building with 0.1 WWR was rotated in a constant increment of 45° clockwise with eight variations in orientation and resulting total heating and cooling energy consumption were obtained from simulation (Fig. 7). Likewise, the effect of WWR and orientation was evaluated by maintaining a constant increment of WWR by 0.1 from 0.2 to 0.9 in eight different orientations.

The result showed that the annual thermal load is minimum when WWR is 0.1 and maximum when WWR is 0.9. It also revealed that, compared to base-case annual energy consumption (16.63 MWh), the consumption decreased by 1.36% for south orientation and increased by 0.23% for north-east orientation when WWR is 0.1. Likewise, the annual thermal energy consumption increased by 5.24% for the south orientation and 7.16% for the north-east orientation respectively when WWR is 0.9. Overall, the result obtained from 72 test scenarios showed that the annual thermal energy consumption increased linearly with an increase in WWR (Fig. 7).

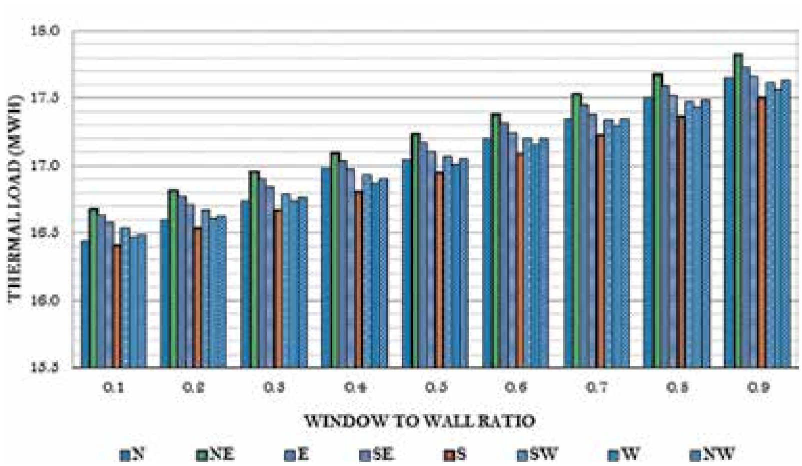

Figure 7: Annual thermal energy consumption (MWh).

The simulated results involving base-case and alternative scenarios revealed that south orientation is best suited and North-East orientation is worst for all WWR in a warm and humid climate, which aligns with the findings from several researchers (Elghamry and Azmy 2017; Nair, Shukla, Shekhar and Jatav 2014). The south as the best orientation for warm and humid climate region is also confirmed by the simulated results of the weather file (figure 3). Likewise, the study also found that increased WWR increases annual thermal load as pointed out in the research by Ghosh and Neogi (2018) and Nair, Shukla, Shekhar, and Jatav (2014).

Generally, it is observed that in a warm and humid climate zone, the south orientation is expected to receive more solar radiation increasing the room heating during summer and heat loss during winter requiring a thermal balance to maintain the comfort level throughout the year. However, the result showed the south orientation as best vis-à-vis less significant variations in thermal loads for both summer and winter. The reason for this could be the consideration of effects of WWR and BO alone instead of considering combined effects of climatic conditions, structural insulation characteristics, façade configurations, and presence of shading devices on energy consumption as observed by Marino et al. (2017). This was also found during the thermal sensation survey in the case area as the respondent living in both north-east and south oriented buildings reported hot inside the building during summer.

5. Conclusions

In this study, the effects of several WWR and orientation strategies applied to a typical case of a residential building in the warm and humid climate of Butwal were evaluated. The analysis and the obtained results showed that south orientation is best for the construction because when south-oriented, a building can save up to 0.2 % of annual thermal load. When oriented towards the north-east, the annual thermal load is increased by 1.31%. When the WWR and orientations were varied to quantify their effects on the building's energy consumption, the result confirmed the annual thermal energy consumption is increased linearly with an increase in WWR. The study concludes that the careful considerations of WWR and the south orientation during designing of the building will contribute to efficient energy consumption in residential buildings.

Since the study was conducted by selecting only one typical case out of the total surveyed house, the results may not be qualified for the generalization. Hence, more studies are needed to include all possible residential typologies prevailing in the case area.

Conflict of Interests

Not declared by authors.

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