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EVALUATION OF ENERGY-COST-EFFICIENT DESIGN ALTERNATIVES FOR RESIDENTIAL BUILDINGS IN KARNATAKA'S TROPICAL WET AND DRY CLIMATIC ZONES

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Abstract
Introduction: The existing building construction techniques in India account for increased operating energy consumption. Due to this, there is a need to apply sustainable construction methods by including passive design techniques. In accordance with the local climatic condition, a good passive design not only maintains a comfortable environment in the house, but also consumes less energy all the while performing the same basic functions as the traditional structures. **Purpose of the study:** The present research focuses on residential villas by analyzing parameters such as illuminance, energy, and cost consumption using Revit (Insight 360) software with two different cases. **Methods:** Considering Case 1 as an existing villa of conventional design and Case 2 presenting a proposed villa, a remodeling of the existing villa with an increased window wall ratio (WWR), different fenestration designs, and a new building plan. The authors followed the Indian Green Building Council (IGBC) guidelines relating to illuminance and generated an analytical energy model using Insight 360 to compare the energy consumption and cost efficiency of the cases. **Results:** The effectiveness of various fenestration types related to direct heat gain, window orientation that would provide more natural light, total operating energy consumption and costs of two different cases of villas are investigated in this paper.

Keywords: Energy and cost consumption, Sustainable architecture, Window wall ratio, Fenestration design.

Introduction

Climate-responsive architecture is defined as building design that is responsive to the local climatic condition. Windows, walls, roofs, and doors are examples of building components. Windows are the only transparent parts of a structure that allow natural light to enter the building. Sunlight is more compatible with the human vision compared to all other forms of lighting since it offers a better lighting environment than electrical lighting sources (Kralj et al., 2019). Building occupants spend more than 90% of their time inside the structure. Interaction between the exterior world and the building interior is thus necessary to increase the cognitive performance of building inhabitants (Jamrozik et al., 2019). Daylight is beneficial to one's health, consciousness, productivity, and sense of comfort, and it plays an important part in the construction. An illumination level of 110 to 2200 lux is adequate lighting to be provided to ensure visual comfort for the occupants, thereby reducing strain on the eyes and associated health impacts (IGBC, 2017). The proximity to any obstruction that may shadow the structure, such as nearby buildings and trees, creates the most difficult design and may have an impact on the distribution of light and solar heat gain in structures. Sustainable building design includes the orientation of a building and the placement of its windows, roofs, and other fenestrations at the site (Baruah and Sahoo, 2020).

Autodesk Revit has applications for architects, drafters, mechanical, structural, and MEP engineers and designers. It is an easy-to-follow tool for enhancing a building's life cycle energy and environmental efficiency. Insight 360 visualizes and interacts with critical performance data, benchmarks, variables, ranges, and criteria for whole-building energy, heating, cooling, daylighting, and solar radiation simulations. This software is a dependable market-leading simulation engine that combines cutting-edge parallel cloud computing techniques that simultaneously simulate multiple potential outcomes. Windows, especially external windows, are irreplaceable building components. People want windows primarily for daylight and secondarily for the view. They have the function of linking indoor and outdoor environments, introducing fresh air and providing better daylight through transparency and openness. It has been reported that energy loss through external windows amounts to 57–63% of total building energy loss (Liu et al., 2019). To reduce such a high energy loss, the application of window shades is essential for fenestration systems to reduce the heating load of buildings as well as daylight discomfort due to glare. Well-arranged window shades could protect the window from excessive solar radiation in summer and allow maximum solar heat gain in winter (Ghosh and Neogi, 2018). A comparison of the performance results of indoor and outdoor shading devices via Energy Plus software showed that using window shades always improves thermal comfort and affects energy consumption (Atzeri et al., 2014). Window shades could effectively reduce the annual air conditioning energy consumption, and the opening mode of window shades also impacts annual air conditioning energy consumption (Tan et al., 2020). Small window sizes ranging between 10% and 20% WWR with the installation of triple-glazed windows are recommended for residential buildings based on design optimization analysis of an apartment building located in a hot and dry region of India (Chaturvedi et al., 2020). Test results on occupant satisfaction concerning the sense of inner space and visual comfort for different window size results showed that participants tend to perceive good visual comfort when the WWR is within 15–30% (Hong et al., 2019). Window features, such as frame and glass options, area, thermal transmittance value, solar factor, and orientation of windows, need to be selected at an early stage of a building design, as they highly influence the environmental and cost performance of buildings (Souviron et al., 2019).

BIM methodology is a project technique that views information as a key relevant factor throughout the project life cycle (Boton et al., 2015). The digital revolution of the built environment and construction sectors is driven by the BIM approach. The importance of BIM as a strategic component for cost, social, and environmental quality, as well as for establishing growth and competitiveness policies in the sector, is recognized by governments and public advocates throughout Europe and the rest of the world (Hermoso-Orzáez et al., 2019; Tang et al., 2019). The standards for designing sustainable buildings include implementing passive design techniques such as building orientation according to site topography, and good fenestration design for reduced heat gain and glare, while increasing natural illumination (Shekhar and Godihal, 2023). An ideal daylighting solution is consistent with careful consideration of the local climate; several authors have focused on room geometry and orientation as the design's first step (Baker, N. and Steemers, 2002; Nardi et al., 2018). Satisfaction with a daylighting design is a complicated subject that is affected by numerous factors such as facade orientation, obstructions, and window direction. When windows are properly oriented, they allow maximum daylight penetration while reducing the need for external lighting systems and introducing complex shading devices (Freewan et al., 2020). Regarding educational spaces, a study has examined light shelves, upper windows, and reflectors in Jordanian educational buildings. The study results showed that by using light shelves or skylights, electricity consumption was reduced in classrooms by an average of 40–50%, and light shelves or rear windows improved uniformity and illuminance levels considerably (Sedaghatnia et al., 2021).

Investigation on optimizing window design decisions to maximize daylighting while minimizing glare and energy use is done by means of Ladybug and Honeybee, Grasshopper plugins for Rhinoceros software; Energy Plus and Dayism engines allow analyzing daylighting and energy performance. A window with no shading consumes more energy per year than a window with light shelves and louvers. Overall, the best shading systems for any climatic building differ depending on the WWR, orientation, and design initiatives (Xing et al., 2022). 40% WWR in a south-facing building facade in a humid subtropical climate setting provides the best energy performance of electrochromic (EC) smart window glazing among other configurations tested with different WWR and orientation. South-facing windows in a hot climate are the best option for reducing total energy loads while maintaining visibility, natural lighting, and comfort (ISHRAE, 2018–2019). The threshold illuminance level for a living room, bedroom, and kitchen is 300 lux, 100 lux, and 500 lux, respectively, according to the second version of ISHRAE (2018–2019).

Hassan is located in Karnataka's tropical wet and dry climate zones. Throughout the year, Hassan city receives an average of 2718.97 hours of sunlight. The city's lowest and highest temperatures are respectively 20.1 and 25 degrees Celsius (en.climate-data.org, 2019). Appropriate use of building energy-saving strategies has a significant influence on building energy efficiency and the socio-economic growth of our current civilization. As a result, it may save a significant amount of building energy, which would be much appreciated in order to reduce GHG emissions and protect the environment from anthropogenic climate change (Akram et al., 2023). An overview of the literature devoted to the topics on energy scenario, green building and retrofitting, and cases of awarded green buildings in Malaysia revealed that buildings were designed taking climate into account in an effort to use less energy overall. The use of passive structural devices and the integration of advanced technologies are strong building characteristics that have their origins in proactive strategies to address environmental and energy conservation problems as well as consideration of sustainability (Mohd-Rahim et al., 2017). One of the elements that must be taken into account when planning a building is energy-efficient building design models. Buildings can use sunlight as a source of natural light from early in the morning until late at night. Utilizing natural light will lower the amount of energy used by buildings. The level of illumination in the workspace has been determined using quantitative statistical descriptive analysis. The distribution of natural light with the building's orientation towards the east was found to be greater than with the orientation towards the south (Jamala et al., 2021).

The accompanying investigation and analysis in this paper are based on a case study of a three-bedroom residential corner villa built using traditional construction techniques. The Revit Insight 360 program was used to evaluate the building's lighting performance including its operating energy and cost consumption. Based on the results of the analysis, the paper proposes a framework for the construction of a single-story residential building based on the chosen locality to maximize illuminance and reduce operating power and cost consumption. The study's criteria include the observation of building residents based on daylight illuminance, a survey of nearby building characteristics, setback distance, and the physical attributes of existing buildings. The following objectives directed the study's implementation:

- To find the ideal plan typology for delivering optimized daylighting through the use of sustainable design techniques by changing the building floor plan, window wall ratio (WWR), and fenestration design.
- To give detailed optimal daylight performance, cost-effective and energy-efficient design standards for the hypothetically modeled single-story residential villa.

Methodology

To validate and apply the recommended sustainable design approach, the authors initially chose a real case study of a 3BHK residential villa building. The structure of this paper has the following three sections. Section 1: three-dimensional (3D) modeling of the existing villa using Revit as per the architecture design and building components. Section 2: the existing villa was remodeled to the advanced design by modifying the building plan, increasing the WWR, and introducing different fenestration designs. Section 3: daylight, energy, and cost consumption of the existing building and remodeled building were analyzed and compared under four different contexts using Revit Insight 360. The analysis was performed under clear skies conditions and at 12 p.m. in the month of September, as recommended by the IGBC. The methodology adopted in this study is shown in Fig. 1.

Fenestrations in the building envelope here are referred to as window shading types. In the context of sustainable design, the choice of fenestration design affects the lighting and energy performance of buildings, as well as the economic aspects of sustainability. Fig. 2 depicts several types of fenestration designs examined for the present research.

Results and Discussion

Existing villa (EV): Case 1

The existing villa has a built-up area of 1650 m^2 encircled by two single-story buildings with two elevations facing the main road and the main entrance door towards the west as shown in Fig. 3.

The villa has been constructed maintaining a minimum setback distance of 1.5 feet as per Hassan City Corporation's recommendation. Table 1 presents the given window wall ratio for each side of the Case 1 structure. Three-dimensional modeling of the clay brick structure and type 1 fenestration design was performed using Revit 2020. The villa's floor-to-floor height is 10 feet; sill height of 3 feet, lintel height of 7 feet, and 200 mm RCC roof were input while designing in Revit based on the survey done by the researchers.

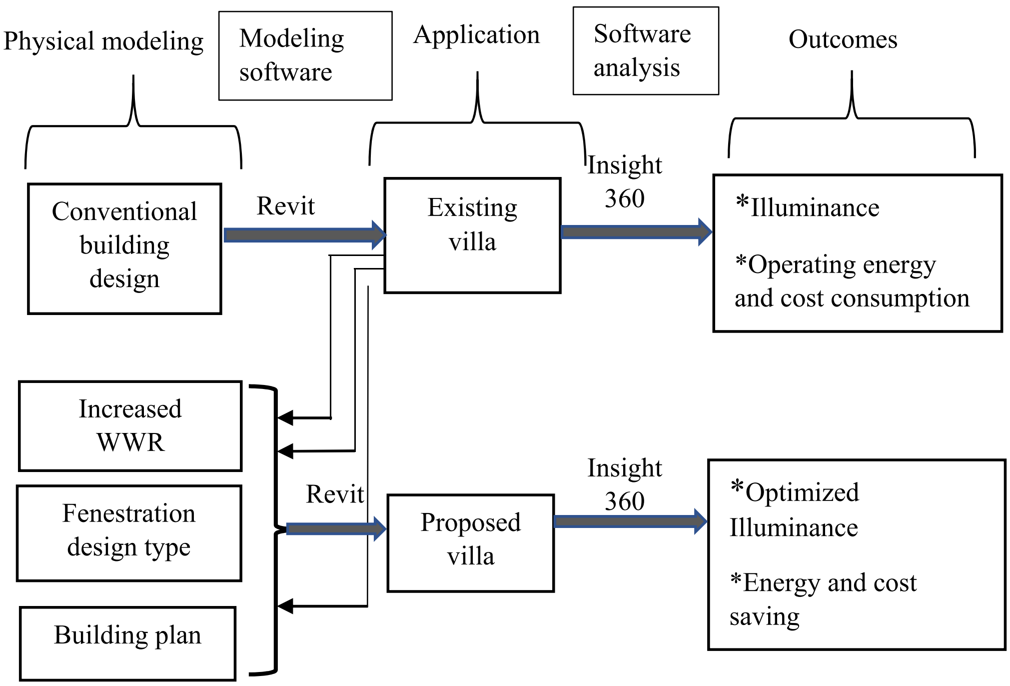

Fig. 1. Methodology adopted for the study

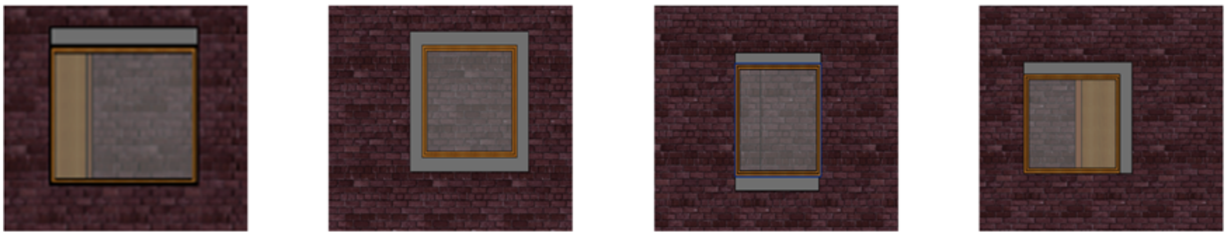

Fig. 2. Fenestration shading types

In the owner-occupied conventional villa, the building envelope includes wall assembly and roof assembly with the values of thermal conductivity and SHGC of glass as shown in Table 2. These building factors control the building energy consumption as a secondary source through heat transfer into the building.

Proposed villa (PV): Case 2

The proposed building design is propounded for the same area of the existing villa while keeping the other design specifications the same. The results are compared in terms of daylight illuminance, operating energy, and cost per square meter per year. Window orientation (WO) and WWR were altered and new fenestration types were introduced in a new villa. Fig. 4 shows a two-dimensional architectural design of a renovated villa with modifications to the building's geometry and window orientation in accordance with Case 1.

The current study suggests a larger WWR for a proposed villa so as to gain more natural daylight and reduce operating energy consumption, and eventually cut the costs. To enable the heat loss via the window to be greater than the heat gain from solar radiation, a mix of different fenestration designs for varying window orientation and dimensions was contemplated while remodeling EV into PV. Under the Case 2 condition, four different contexts with various fenestration types, window orientation, and WWR were considered as indicated in Table 3.

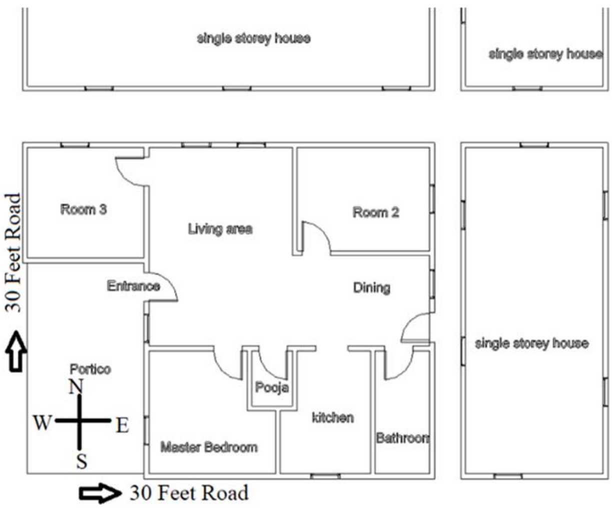

Fig. 3. Existing villa floor plan

Table 1. **Window wall ratio of Case 1**

Window orientation	Window wall ratio
East side	11%
West side	12%
North side	7%
South side	4%
Mean WWR	8.5%

Table 2. **Thermo-physical characteristics of case study building**

Property	*Values*	*Abbreviation*
Location	Hassan 24.9025° N, 67.0729° E	R= Thermal resistivity
Clay brick	$U=3.543 W/m^2K$, $R=0.382 m^2K/W$	SHGC= Solar heat gain coefficient
Plane glass	SHGC=0.78	U=Thermal conductivity
RCC roof	$U=2.61\ W/m^2K$, $R=0.282\ m^2K/W$	

Daylight characteristics

Case 1: Illuminance

The luminous flux per unit area in Case 1 was found to be less than the illuminance threshold of 110 lux. The grouping of lux at different parts of the house is shown in Fig. 5. Since the portico is open, it receives up to 800 lux, which is more sunlight than in any other part of the house. A portion of room 2 and the dining area, which are located behind a one-story building, receive up to 2200 lux. It is observable that designing windows in the south is more effective than planning openings in other directions. Fig. 6 depicts the range of illuminance per unit area characteristic of the case study villa. Illuminance evaluation using Insight 360 is done following the steps below:

Case 2: Illuminance

The authors remodeled Case 1 by changing the house floorplan, installing larger windows, and combining four different fenestration types. Thus, the proposed villa would receive illuminance greater than the existing villa ranging from 107 to 2200 lux of total natural light. The luminous flux per unit area (lux) in Case 2 in all four contexts is shown in Figs. 7–10.

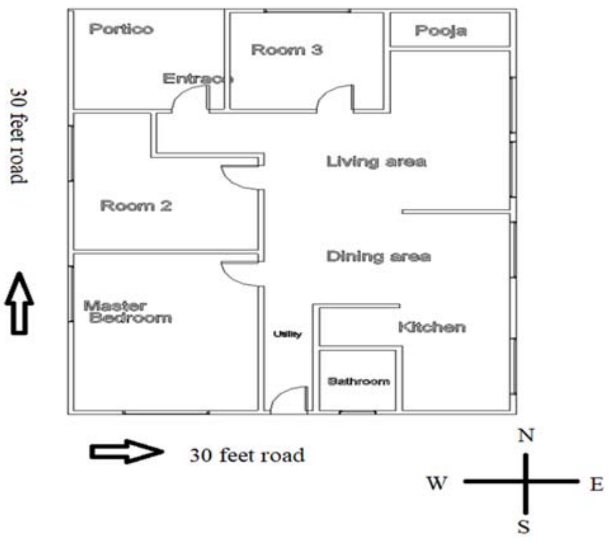

Fig. 4. Proposed villa floor plan

Contexts 3 and 4 provide greater illuminance than Contexts 1 and 2, but they fail to meet the IGBC criteria for visual comfort due to glare. In case of Context 1, about 50% of the modeled area receives up to 2071 lux.

Fenestration type attributes — energy consumption

Aside from maximizing daylight penetration, a good fenestration design is required to reduce the energy demand of buildings by dissipating the direct heat gain and giving glare-free light. Window orientation, WWR, and fenestration design type factors play important roles in limiting the potential heat gain by any structure, hence energy consumption related to fenestration is proportionate to these three factors. Operating energy consumption for a combination of window direction, area, and fenestration design type in Case 2 compared to Case 1 is expressed in Fig. 11.

For all four of the investigated fenestration types and as demonstrated in Table 3 and Fig. 10, energy consumption is considerably lower in the south direction up to 12.5% WWR than in the other three directions. Despite the fact that the WWR is relatively lower, type 2 fenestration is a worse combination for the north side. Larger windows (up to 20%) in the east direction and west-orientated windows with >10% WWR should be installed with type 3 fenestration for the ideal

Table 3. **Details on Case 1 and Case 2**

		Case 1	**Case 2 Proposed villa**				**Case 2 Mean WWR**
Direction	**Variants**	**Existing villa**	**Context 1**	**Context 2**	**Context 3**	**Context 4**	
East	Fenestration	Type 1	Type 1	Type 3	Type 2	Type 4	
	WWR (%)	11	13	20	12	10	13.75%
West	Fenestration	Type 1	Type 4	Type 1	Type 3	Type 2	
	WWR (%)	12	9	10	15	16	12.5%
North	Fenestration	Type 1	Type 2	Type 4	Type 1	Type 3	
	WWR (%)	7	11	12	10	13	11.5%
South	Fenestration	Type 1	Type 3	Type 2	Type 4	Type 1	
	WWR (%)	4	12	7	14	18	12.75%
Mean WWR		8.5%	11.25%	12.25%	13.25%	14.25%	

Fig. 5. Existing building illuminance

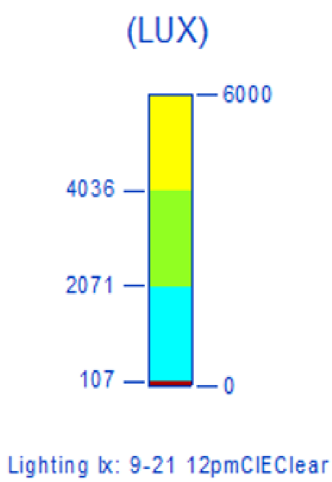

Fig. 6. Lux range

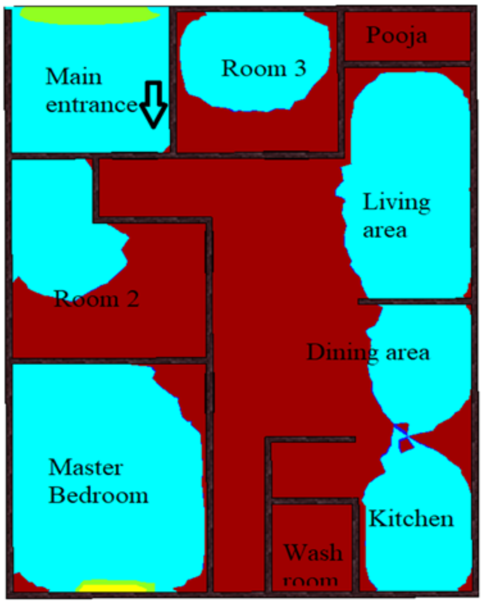

Fig. 7. Case 2 — Context 1

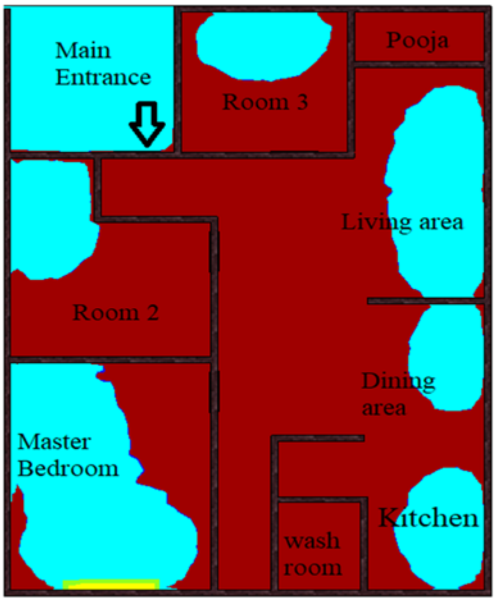

Fig. 8. Case 2 — Context 2

solution of gaining maximum illuminance and reduced heat transfer.

Window orientation attributes — energy demand

As the WWR increases from Case 1 to Case 2 in different contexts, energy consumption is decreasing as seen in Fig. 12. South-facing windows are the most preferable in terms of saving energy followed by north and east orientation. In the case of west-facing windows, energy demand increases as the heat gain through west windows is considerably higher than in the other three directions. For substantially identical WWR, windows on the north side of the building will use more energy and have high potential of transmitting heat than those in the east. Large south-facing windows are more energy-efficient with respect to daylight, heat, and cooling effect compared to other window orientations.

Behavior of Case 1 and Case 2

A comparison of relative cost and energy consumption between conventional method and sustainable construction technique is presented in Table 4 by taking a building case study. The operating energy cost estimated by Insight 360 is described in terms of cost per unit area per year. The cost and energy accredited to Case 1 and Case 2 imply that adopting the sustainable construction method like the efficient design of a building according to its geographical condition would help in the natural

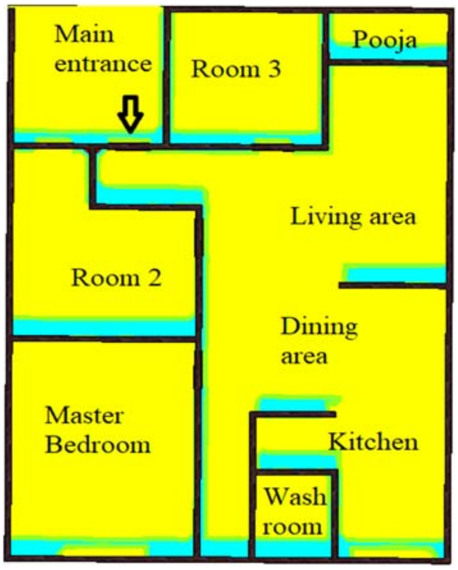

Fig. 9. Case 2 — Context 3

Fig. 10. Case 2 — Context 4

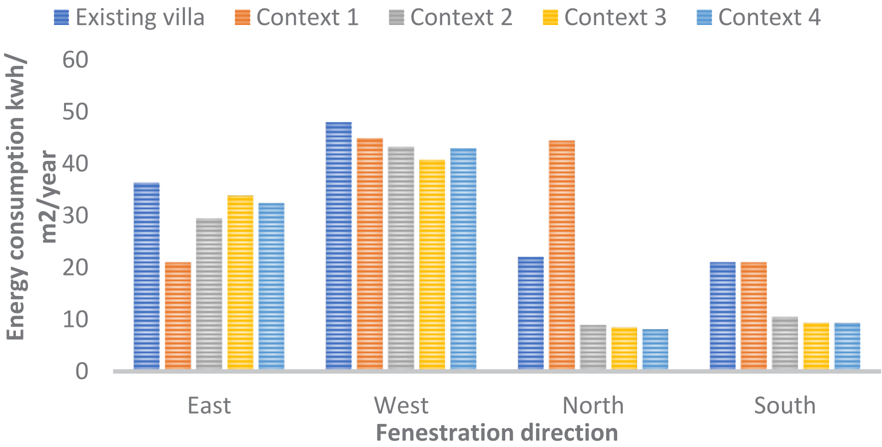

Fig. 11. Energy pattern of EV and PV as for fenestration

Fig. 12. Energy pattern of EB and NB as for window orientation

energy utilization of the building rather than getting energy using an external source.

Conclusions

Revit and Insight 360 will aid in creating cost-effective and energy-efficient building designs for specific locations and designing energy-efficient structures. The existing villa was designed for 8.5% WWR and is receiving 108 lux of natural light within the building. As the Green Rating for Integrated Habitat Assessment (GRIHA, India) suggests a minimum of 10% WWR provided in building design, the authors propose an increase in WWR, which increased the intensity of light in a range of 108–2200 lux in the majority of the residential area. Context 1 of the proposed villa design has optimal daylight illuminance ranging within 108–800 lux and approximately 10% energy saving is achieved thanks to the increased WWR and unique shade type. Type 3 fenestration is revealed to be a powerful design maximizing illuminance, which nonetheless requires additional adaptation to satisfy subjective criterion of visual comfort of the occupants. A switch to south-facing windows is also a beneficial solution to counter heat gain.

Table 4. **Comparison of energy consumption for EV and PV**

Building variants	Study contexts	Cost INR/m²/year	Energy KWh/m²/year
Case 1	Existing villa	1653	293
Case 2	Context 1	1479	258
	Context 2	1510	265
	Context 3	1520	270
	Context 4	1542	267

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ОЦЕНКА ЭНЕРГЕТИЧЕСКОЙ И ЭКОНОМИЧЕСКОЙ ЭФФЕКТИВНОСТИ АЛЬТЕРНАТИВНЫХ ДИЗАЙНОВ ЖИЛЫХ ЗДАНИЙ В ТРОПИЧЕСКИХ ВЛАЖНЫХ И СУХИХ КЛИМАТИЧЕСКИХ ЗОНАХ ШТАТА КАРНАТАКА

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Аннотация
Введение: Существующие технологии строительства зданий в Индии приводят к увеличению энергопотребления. Это вызывает необходимость применения методов устойчивого строительства, в том числе пассивных методов проектирования. Соответствуя местным климатическим условиям, хорошая пассивная конструкция не только поддерживает комфортную среду в доме, но и потребляет меньше энергии, при этом выполняя те же основные функции, что и традиционные конструкции. **Цель исследования:** Данная работа посвящена исследованию жилых вилл путем анализа таких параметров, как освещенность, энергопотребление, экономическая эффективность с использованием программного обеспечения Revit (Insight 360) на примере двух кейсов. **Методы:** Кейс 1 представляет собой реально существующую виллу традиционного дизайна, а Кейс 2 предлагает модель реконструкции существующей виллы с увеличенным соотношением площади окон к площади стен, различными конструкциями окон и новым планом здания. Авторы следовали рекомендациям по освещенности Индийского совета по экологическому строительству (IGBC) и создали аналитическую энергетическую модель с помощью Insight 360 для сравнения энергопотребления и экономической эффективности кейсов. **Результаты:** В этой статье исследуется эффективность различных типов окон, связанная с прямым притоком тепла, ориентацией окон, обеспечивающей больше естественного освещения, общим эксплуатационным потреблением энергии и затратами в двух разных случаях вилл.

Ключевые слова: энергопотребление и затраты, устойчивая архитектура, соотношение площади окон к площади стен, проектирование окон.