Original Research

Sustainable Consumption Patterns Adopting BIM-Enabled Energy Optimization - A Case Study of Developing Urban Centre

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Abstract

Population and urbanization have resulted in increased demands of high-rise buildings to meet the spatial challenge. However, energy consumption by high risers have become a serious concern, especially in developing countries. Supporting the 2030 agenda for sustainable development needs improvement in energy efficiency at global as well as local levels, thus requiring proper sustainable consumption patterns. The current work explores an innovative approach to optimize the operational energy consumption utilizing building orientation at the design stage. A 3D parametric BIM model of a sixteen-story high-rise building was analysed for the proposed location. A rotation scheme with an angular increment of 45° was devised to observe the energy consumption patterns. The energy analysis and Building Energy Quotient (bEQ) level observed energy-intensive pattern at the proposed orientation. For the rotation scheme analysed, almost 70% achieved a "Poor" rating of bEQ, whereas the remaining were at "Fair" level. Rotating the building's face in the West \rightarrow North or East \rightarrow South direction, annual energy consumption pattern observed a decreasing trend and vice versa. Rotation 02 (45°) resulted a minimum annual energy consumption was further optimized opting certain design parameters, thus resulting in an overall annual energy saving of almost 64%. This improved rating scale from a Fair to "Very Good" status, also meeting the challenge of Architecture 2030. The study observed proper orientation-based energy analysis of the built environment at the design stage offers promising prospects for optimized consumption patterns for sustainable developments.

Keywords: energy analysis, optimization, sustainability, building information modelling, performance analysis, building energy modelling

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Introduction

Climate change due to global warming presents serious issues threatening the survival of mankind [1]. Population growth, improved and high living standards in building facilities have elevated energy usage [2]. The global energy consumption unveiled that energy demand is rising continuously. Samuel, Joseph-Akwara [3] reported 1/3rd increase in global energy demand from 2020 to 2035. Recent trends in energy consumption had raised significant concerns about its impacts on the environment, supply chain and energy exhaustion at a global level [4]. The building industry utilizes a substantial amount of share in this [5]. According to US Energy Information Association, the construction industry accounts up to 20.1% of the global energy consumption [6]. Collectively, the construction and built structures remain responsible for 36% of total energy consumption and 40% of CO₂ emissions [7]. As per Tushar, Bhuiyan [8], the housing sector contributed up to a 27% of overall energy consumption with 17% of CO, production globally. Jin, Zhong [9] reported 20% to 40% of total energy consumption worldwide due to the building sector with $1/3^{rd}$ share in greenhouse gas release. Several researches on energy analysis have concluded that the overall energy required in the life cycle of the buildings range from 10% to 20% for the embodied stage, whilst 80% to 90% for the operational period [10]. A significant portion of the energy was utilized for improving quality of living and indoor built environment. However, lack of coordination during the design process was observed to be serious barrier for modifying building or structure to attain performance criteria [11]. Energy Analysis (EA) or energy assessments during the early design phase of building projects would significantly enhance and support sustainable development goals [12].

Recent advancement in digital technology innovations have played a vital role in AEC industry that cannot be overlooked. Besides many other supporting systems, BIM-enabled energy optimization supported by modeling energy analysis can help to minimize the energy-related environmental impacts and support to solve problems related to consumption patterns. The energy performance analysis for buildings can be performed at the planning stage through smart and parametric simulated virtual illustrations [13]. It has become possible to integrate energy-efficient techniques into building design, improve performance and generate energy simulations with high accuracy [14]. Thus, BIM has provided a platform through simulation technology and inter linked processes to generate, communicate and analyse building models in real time situations [15]. This platform advocates maximizing efficiency and quality by reducing time effort [16]. Somboonwit, Boontore [17] argued that approximately 20% of total cost savings could be possible in the BIM-enabled sustainable construction of the building. However, the efficient designs and the interaction of Building Information Modeling (BIM) to Building Energy Modeling (BEM) remains a non-linear and multiplex concern. Hence, an accurate and useful output would require an inclusive prescription or guidance [18]. BIMbased energy modeling tools have also been adopted to predict energy savings in the design stage of lowenergy buildings [19]. At the conceptual design phase, professionals could assess many alternate designs to optimize and choose vital energy approaches which may prove critical in sustainable development.

According to Asl, Bergin [20], the energy modeling tools currently used for simulating buildings lack their support to establish parametric relations with the building objects. Besides many other various parameters for energy consumption for buildings, the orientation is an important parameter to achieve energy efficient design [21, 22]. Xu, Mumford [23] reviewed a substantial impact of building orientation on its energy performance. This limitation has been managed by the BIM innovations thus ensuring sustainable building designs. Its ability to assess energy performance for different alternates offer promising energy saving prospects. BIM can equip construction industry professional with proactive strategies to ensure minimum energy consumption levels during life cycle [21].

Reza Soroush and Amani [24] conducted a study for design optimization of a high-rise building located in the Gilan province, Iran. The main focus was to optimize the design and energy performance with respective cost saving. Case study was developed in BIM environment to assess the energy performance. Three design model created with simultaneous combination of building components (conceptual masses) were analysed. The virtual environment of BIM supported the objectives of the study. With such parameters a saving of almost 26% was achieved in energy use intensity (kWh/m²/year). However, the orientation of the building remained the same in all cases. Sandberg, Mukkavaara [25] proposed a BIM based optimization model for life cycle energy for a mutli-family residential building in Sweden. The study observed the orientation of the building as an important design variable with possible impact on energy. It was advised to investigate this parameter for future research to achieve optimised energy design solutions. According to Abanda and Byers [26], orientation has substantial impact on energy needs which should be explored. Their study investigated the BIM models developed for a 3-storey house located in Hertfordshire, UK. Various test with 45° orientational increments were conducted. The orientation at 180° was observed the best whereas 45° the least conserving position. Results showed that proper orientation could save energy worth up to £878 throughout its lifetime. Kim, Zadeh [27] investigated the impact of window size, position and orientation of a two-storey single family house using BIM model. The study observed a small variation in energy load. This was reasoned due to very small scale of case study opted. It was recommended that bigger scaled building

should be analyzed to achieve considerable results. Watfa, Hawash [21] explored a case study of a single storey family house in UAE to investigate the impact of design factors like orientation, window glazing and size of the building on the energy consumption. The BIM and BEM models were simulated with different parametric combinations to observe minimizing the overall energy consumption trend. Using 3D virtual environment, the study achieved a maximum reduction of 8% at an orientation of 180 degrees from North. However, each orientation was just observed for energy patterns and further optimization was not considered. Similarly, Yarramsetty, Rohullah [28] performed a simplified analysis to observe the effect of orientation on energy cost levels for a multi-story residential house located in Afghanistan. BIM was adopted to simulate the housing unit in 3D environment. 24 orientations with an increment of 15° were analysed. The rotation at 315° achieved the maximum energy cost. In this case also, each orientation was only observed for energy cost considerations without any concerns for optimization.

Various researchers have explored the impact of orientation on different facilities. However, these studies were mostly limited to housing units with maximum three storey height. In addition, only energy assessments or energy cost savings at different orientations were explored. The optimization of these orientation still remains a grey area that can result in further energy saving and lower the consumption patterns for sustainable infrastructure developments. The optimization strategies offer a great potential to achieve reduction in energy consumption patterns [29]. The ability of BIM to optimize the location and orientation at the design stage has enabled the designers and engineers to meet the sustainable development challenges [30].

Pakistan, being a developing country, has been experiencing serious energy crises. A 30% difference in supply and demand of electricity has been reported recently [31]. The estimated electricity demand is expected to rise at a continually raising yearly growth rate of 5% to 7% from 2010 to 2030 [32]. With the everincreasing population and urbanization, the primary accommodation demand would be met through the high-rise residential building as space constraints are becoming a matter of concern. However, the energy consumption patterns for buildings have been observed to be irregular due to several factors, including the building's size, building type, seasonal variations and occupants behaviour patterns etc. The adoption of energy control measures remains one of the key aspects to achieve less energy consumption patterns [22]. Innovative approaches, in the newly planned built environment as well as in existing infrastructure, would be the key to meet the challenges of such energy concerns. The current study aims to propose a simulated approach in a virtual environment to assess and optimize the energy consumption pattern of multistorey building at early phase. The energy savings would result in lowering the financial aspect of energy expenditures with an indirect reduction of carbon footprint. This would also help to educate our industry professional regarding the Goal 07 of 2030 agenda for developing a sustainable society [33].

Methods

A sixteen (16) story commercial building was selected for BIM-based energy analysis and energy optimization patterns. The 3D virtual BIM model was developed, Fig. 1. According to National Building Information Modeling Standards (NBIMS), BIM is defined as "the digital representation of physical and functional characteristics of a facility".

After model completion, energy simulation and analysis were performed on conceptual design attributes of the facility using Insight 360. The BIM model was transformed into Building Energy Model (BEM) to determine energy usage with a critical objective to achieve sustainable energy consumption decisions. Thermal zoning of the model according to the geometry, was created to observe the constituents of the analytical model and conduct the Cloud-based energy analysis. The proposed geometry is 37° clockwise w.r.t True North, Fig 2. Cloud-based Energy analysis was performed by rotating the building in a circle (360°) with a lap interval of 45°[26].

The geographical location of the energy model is one of the essential aspects of analysis. To achieve a realistic picture, the proposed building's exact location was included before proceeding to cloud computing analysis. The cyclic cloud computing process was required to be repeated with each rotation pattern, Fig 3.

Eight different orientations considering the centreline of the building were adopted. In line



Fig. 1. Revit 3-D Model.

True North Orientation $\frac{1}{10^{\circ}}$ 315° 315° 315

Fig. 2. Proposed orientation of the building along with rotation mechanism.



Fig. 3. Cloud Computing Cycle.

with the guidelines provided by ASHRAE Building Energy Labelling Program Implementation Report 2009, Building Energy Quotient (bEQ) was calculated using Eq. (1)

$$EnergyQuotient(EQ) = \frac{EUIActual}{EUIMedian} \times 100$$
(1)

Fig. 4.(a-b) present the bEQ labels the buildings based on a numerical and qualitative score. The achieved scale was compared with the standards for improvements for an energy-efficient facility.

Energy optimization corresponding to energy utilization was performed which led to maximum energy saving, thus minimizing the consumption patterns and ultimately promoting sustainable developments. This optimization before the construction initiation could help to achieve energy-efficient facilities and scale down the energy utilization while maintaining the same comfort level and quality of life for users. Energy efficient buildings also remains one of the key agenda of Architecture 2030 challenge. Table 1 details the factors and their corresponding optimization ranges used during the energy analysis and optimization. The energy optimization has been performed through Insight 360 which works on cloud-based analysis mechanism. This cloud-based analysis provides us with sixteen parameters / factors to achieve optimization for any target case study.

Results and Discussions

The 3-D virtual parametric model was transformed into an energy model to perform analysis using Insight360 to study the energy pattern. Fig. 5. presents transformed energy model, BEM.

Energy analysis was performed on eight orientations with an aim of obtaining the energy consumption at each specified orientation along with the baseline orientation of True North.

The average energy consumption achieved at true North orientation was 282 kWh/m²/yr with an upper limit of 971 kWh/m²/yr and a lower limit of 57 kWh/m²/yr, Fig 6. According to ASHRAE 90.1 benchmark value was 265 kWh/m²/yr.

Based upon the output of energy analysis at respective orientations, a comparative assessment for the achieved energy trends was established. Fig. 7. shows the output of this comparative analysis. The average energy consumption was 276 kWh/m²/yr with a standard deviation of 6.2. At Rotation 08 (315°), the highest energy consumption was observed whereas Rotation 02 (45°) achieved the least value in this



Fig. 4. a) ASHRAE bEQ Scale b) ASHRAE Building Energy Quotient Label.

Table 1. Energy Optimization parameters range.

Sr. No.	Factors	Optimization Range available
01	Orientation	0°- 360° with a lap of 45° (8 Rotations)
02	Annual energy usage	Simulated Value
03	Window Wall Ratio	95% - 0%
04	Window shades	1/6, 1/4, 1/3, 1/2 and 2/3
05	Window glass	Sgl Clr, Dbl Clr, Dbl LoE, and Trp LoE
06	Wall construction	Uninsulated, R13-Wood, R13-Metal, R2-CMU, R38-Wood, 14-inch-ICF, 12.25-inch-SIP, and R13+R10 Metal
07	Roof construction	Uninsulated, R10, R15, R19, R38, 10.25-inch-SIP and R60
08	Infiltration	2.0, 1.6, 1.2, 0.8, 0.4, 0.2 and 0.1 (ACH)
09	Lighting efficiency	20.45, 16.15, 11.84. 7.53 and 3.23 (W/m ²)
10	Day-lighting and Occupancy Control	None, Daylighting Control, Occupancy Control, and Daylighting & Occupancy Control
11	Plug load efficiency	27.99, 21.53, 17.22, 13.99, 10.76 and 6.46 (W/m ²)
12	HVAC	ASHRAE VAV, ASHRAE Package System, High Eff. VAV, High Eff. Package System, High Eff. Package Terminal AC and ASHRAE Package Terminal Heat Pump
13	Operating schedule	24/7, 12/7, 12/6 and 12/5
14	PV Panel efficiency	16%, 18.6% and 20.4%
15	PV Surface coverage	0%, 60%, 75% and 90%
16	PV Payback limit	10 yr, 20 yr, and 30 yr



Fig. 5. Insight Energy Model.

regard. The true North, set as baseline location, was also observed on the higher side of the consumption level. Two further consumptions comparison were performed, one among the consecutive rotations with each proceeding rotation and the second, baseline against each orientation. Table 2 provides the summary of comparison.

It was learned that out of eight rotations, only two (R04 and R08) depicted higher consumption patterns in comparison with the baseline. In other words, higher values of these rotations suggested the unsuitability of these rotations for practical considerations. Furthermore, a critical analysis revealed a decreased annual energy trend at both the East-South and the West-North orientations. In contrast, the North-East and South-West sides observed an upward trend in energy assumptions. The energy efficiency patterns were further investigated by the Building Energy Quotient (bEQ). In conventional construction, almost 70% of rotations resulted in a score of more than 100. According to ASHRAE, a score more than 100 presented inefficiency in energy consumption and thus, labeled as "Poor". Table 3 shows the status of each orientation in this regard.

Based upon the above findings, rotation 02 at 45° angle presented the most suitable opportunity to maximize the energy savings. Hence this orientation was further investigated through optimization analysis.



Fig. 6. Energy consumption at true North.



Fig. 7. Benchmark Comparison.

Description / Orientation	Rotation	R-01	R-02	R-03	R-04	R-05	R-06	R-07	R-08
Description / Orientation	True North	0°/360°	45°	90°	135°	180°	225°	270°	315°
Consecutive Variations	-	6	9	-4	-12	5	9	-7	-8
Variation w.r.t True North	-	-6	-15	-11	1	-4	-13	-6	2

Table 2. Average Energy Consumption Statistics with 360° Rotation Cycle.

Table 3. Building Energy Quotient (bEQ) as per ASHRAE

Decorintion	hEO Saara	bEQ Rating			
Description	DEQ Scole	Scale	Label		
True North	102.17	D	Poor		
Rotation 01	100.00	D	Poor		
Rotation 02	96.74	С	Fair		
Rotation 03	98.19	С	Fair		
Rotation 04	102.54	D	Poor		
Rotation 05	100.72	D	Poor		
Rotation 06	97.46	С	Fair		
Rotation 07	100.00	D	Poor		
Rotation 08	102.90	D	Poor		

To achieve this, different factors affecting consumption patterns were considered. The best possible combination was selected to achieve the maximum results. The 45° building was optimized due to the lowest energy utilization value. The most realistic values, according to basic building features and specifications, were chosen for optimization. Table 4 presents the details of parameters opted for energy optimization in the study.

Actual window to wall ratios was chosen according to building design and drawings. For wall, the actual construction made up of blocks and plaster was selected. Similarly, for roof, a RCC (reinforced cement concrete) slab was considered. The infiltration rate as per the actual openings of building was applied. A plug load efficiency of 6.46 and a conventional six day a week with 12 hours operating schedule was chosen. The payback period of 30 years was considered. The peculiar behaviour in compliance with ASHRAE 90.1 has been elaborated with an optimized value of 97 kWh/m²/yr in Fig. 8.

The highest optimization was observed for the HVAC factor with a total reduction of 39 kWh/m²/yr in energy consumption. Thus, it contributed 23% in overall energy savings. Factors like the facility's orientation, WWR (window to wall ratio), window shades, lighting efficiency and operating schedule were amongst the other significant contributors in energy reductions. The orientation adjustment reduced the consumption by 18 kWh/m²/yr (10.50%), WWR of Eastern wall, and window shades collectively reduced 30 kWh/m²/yr (17.65%). Strict implementation of an electricity operating schedule of 6 days in a week with 12 workings hours per day helped reduce energy

Table 4. Summary of Optimization Analysis

Factors	Selected Settings				
Benchmark	267 kWh / m ² / yr				
Orientation	45°				
WWR - Southern	16%				
WWR - Northern	14%				
WWR – Western	29%				
WWR - Eastern	20%				
Window Shades - South					
Window Shades - North	1/2 Win Height				
Window Shades – West					
Window Shades - East					
Wall Construction	BIM				
Roof Construction	R38				
Infiltration	0.285 ACH				
Lighting Efficiency	7.53 W/m2				
Daylighting & Occupancy Controls	Occupancy Controls				
Plug Load Efficiency	6.46 W/m2				
Operating Schedule	12/6				
PV - Panel Efficiency	18.60%				
PV - Pay Back Limit	30 yr				
PV - Surface Coverage	60%				

consumption by 8.80% (15 kWh/m²/yr). Overall, a total of 170 kWh/m²/yr energy saving was achieved. Based upon the optimization strategy for this particular study, the building successfully qualified for the bEQ rating of "Very Good" at this orientation.

Conclusions and Recommendations

The scope of this research work was limited to a case study of commercial buildings, and only the operational phase was considered. The objective was to promote the optimization of the energy patterns in buildings by utilizing their orientation attribute. The energy analysis was performed by proposing a complete circular orientation scheme with a lap interval of 45° for virtually developed prototype model of a high-rise building in a 3D environment. The results concluded that:



Fig. 8. Energy optimization achieved based upon parameters selected.

- Building orientation plays a vital role in energy consumption patterns and presents promising prospects for achieving optimized energy consumption. For eight different orientations, the annual energy ranged between 267 to 284 kWh/m² with a standard deviation of 6.2. Among all, Rotation # 08 (315°) was observed with the highest annual energy consumption whereas Rotation # 02(45°) remained the least.
- Orientation along East to South and West to North highlighted was observed declining trend in energy usage patterns in comparison with the North to East and South to Westside orientation.
- Six orientations out of eight achieved a "Poor" bEQ scale highlighting that these orientations were energy extensive. The remaining two were scaled as "Fair".
- Rotation 02 (45°) was selected and further optimized by adopting different energy optimization factors related to the design provisions. An optimized value of energy 97 kWh/m2/yr was possible to achieve results more than 60% saving for overall consumption. The HVAC was dominant in achieving a total energy saving (23%) along with window to wall ratio and window shades (17.56%), orientation (10.50%) and daylighting control provisions (8.80%).
- The reduction in energy consumption levels improved the bEQ rating scale from "Fair" to "Very Good" status.

The study concluded that simulations for the building energy usage patterns using virtual technology can help in achieving energy-efficient buildings. Thus, enabling the construction professionals in finalizing the design that promotes optimum energy and ultimately the sustainable development. The orientation of the building plays a vital role in energy conservation patterns. So, it is suggested that an analysis of such type during the planning phase can help to achieve an optimized energy consumption solution which would not only result in energy savings throughout the life cycle of the building but also offset a substantial amount of environmental impact in terms of operational carbon footprint. For a country with a severe energy crisis, the adoption of virtual technology along with the optimized utilization patterns at an early stage of design conception could help to reduce energy usage. Thus, making it possible to achieve the development of sustainable buildings for future generations.

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Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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