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CASE STUDY

Exploring the Potential of Value Engineering to Reduce the Economic Pressure on the Construction Industry in the Case of Luxury Housing

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Abstract

This research highlights the critical role of value engineering in integrating economic sustainability and environmental stewardship within the luxury housing market. It focuses on reconciling profitability with sustainable practices through a comprehensive study of alternative construction materials, their environmental impacts, costs, and long-term financial benefits. A case study on a luxury villa in New Beni-Suef, Egypt, demonstrates the practical application of these principles. The study employs a multi-dimensional approach, including quantitative material selection, environmental performance evaluations using Design Builder software, market research for cost-effective materials, and analysis of long-term electricity costs. It showcases value engineering as essential for economic resilience and environmental sustainability in luxury real estate development, marking it as a pivotal strategy for the sector's future.

Keywords: Construction materials, Design builder, Environmental performance, Value engineering

1. Introduction

Globally, construction contributes ~7% to the GDP and employs over 10% of the workforce, yet it also bears a substantial environmental burden, accounting for 40% of global energy consumption and 23% of greenhouse gas emissions. As the industry grapples with its environmental impact, emerging economies experience unique challenges that necessitate innovative solutions (LLC, 2022; Al-Aees, 2022). Consequently, the Egyptian construction industry faces challenges that demand a nuanced approach to balancing economic and environmental considerations.

In Egypt, the construction landscape is marked by a pronounced rise in building material costs, exemplified by soaring steel and cement prices within a short span (LLC, 2022; Al-Aees, 2022). This surge, exacerbated by the global increase in energy costs, presents a significant economic hurdle for real estate developers, making it increasingly challenging to control costs and remain competitive in the market. The strategic application of value engineering (VE) is crucial to address this economic predicament. VE, a systematic methodology, enables developers to optimize project components, identify cost savings, and enhance overall project value, providing a means to navigate fluctuating material costs and economic uncertainties (Zimina et al., 2012; Elhegazy, 2020; Gyadu-Asiedu et al., 2002).

Simultaneously, environmental sustainability has become a paramount concern for real estate developers in Egypt (Desouki et al., 2024). Policies and regulations aimed at reducing environmental impact are increasingly implemented, necessitating the adoption of sustainable construction practices (Yang et al., 2022; Bergek and Berggren, 2014). However, incorporating energy and water-efficient

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materials and techniques can incur up to 40% higher initial costs than conventional methods, creating a delicate balance between sustainability goals and financial realities (Muth, 2018). Striking a delicate balance is key to achieving sustainability goals without sacrificing financial stability (Rapoport, 2014). The environmental challenge extends to the energy consumption patterns in the residential buildings sector, notably in luxury housing. With the domestic residential sector accounting for the largest share of electricity consumption at 41.7%, there is a growing need to address the environmental impact of high energy consumption, especially in hot, arid climates. The study emphasizes the significance of reducing energy consumption through efficient insulation and energy-saving technologies, offering potential solutions to mitigate the impact of climatic conditions on electricity bills (El-Markaby MS, 2021; William et al., 2021).

Accordingly, the Egyptian construction industry stands at a critical juncture where economic viability, environmental responsibility, and innovative solutions intersect (Siraj and Fayek, 2019). The introduction of VE addresses economic challenges by optimizing projects, while the imperative for environmental sustainability calls for adopting efficient construction practices (Islam et al., 2015). The unique context of Egypt, with its specific climatic challenges and economic dynamics, further emphasizes the need for a framework that integrates economic and environmental sustainability to ensure the resilience of the construction sector in the region.

This research aims to pioneer a comprehensive framework for applying VE in high-class construction real estate projects in Egypt, specifically within the governorate of Beni-Suef. This framework incorporates advanced simulation techniques to scrutinize energy consumption patterns systematically. The primary objective is to integrate simulation results with initial project values, enabling a holistic examination of the potential reductions in energy consumption. The research endeavors to optimize these high-class projects' economic and environmental performance by involving VE principles with simulation-driven analysis.

The framework envisions a multifaceted approach where VE is employed to analyze and optimize various components of the construction process, including material selection, construction techniques, and overall project design, aiming to achieve cost efficiencies without compromising quality or functionality. The simulation introduces a dynamic layer, allowing for the meticulous examination of energy consumption patterns within the specific climatic context of Beni-Suef, a critical consideration in a region characterized by a desert climate and rapid population growth.

The research aspires to contribute to the efficiency of high-class construction projects in Beni-Suef and the broader discourse on sustainable construction practices in emerging economies, where the intersection of economic and environmental considerations demands innovative and integrated solutions. Ultimately, the proposed framework seeks to pave the way for more resilient, cost-effective, and environmentally conscious real estate development in the Egyptian context. The case study in this research is located in the Beni-Suef governorate, where active participation in a national initiative for smart green projects underscores the imperative of protecting the environment and using resources responsibly (Badr). However, the research comprehensively compares commonly utilized construction material alternatives for building envelopes in Egypt. This comparative analysis delves into these material alternatives' environmental performance, initial costs, and long-term expenses.

2. Methodology

This research aims to investigate the potential of VE in determining the feasibility of selecting sustainable materials in the construction industry, as shown in Fig. 1. The first step of the methodology is to choose a relevant case study, which will be a high-class villa in Beni-Suef, Egypt. The key elements that impact the feasibility of choosing sustainable materials will then be identified. These elements include the external wall, window glass, roof insulation, window shading, building orientation, opening area ratio, and facade paint color. Next, different alternatives for each element in the Egyptian market will be selected. After that, the initial costs for the cost-estimable items will be estimated. Building simulation using DesignBuilder software will be conducted to calculate the energy consumption of different alternatives, considering factors such as climate, occupancy, and activity.

DesignBuilder is a widely adapted simulation software. The robustness and adaptability of EnergyPlus, the core simulation engine, allow for detailed building modeling, which is crucial for precise performance analysis (Galiano-Garrigó et al., 2021; Dave Cocking). Studies have shown that DesignBuilder is accurate in predicting the climatic performance of a building (Baharvand et al., 2013). Although some studies questioned the credibility of DesignBuilder compared with actual measurements, they confirmed the feasibility of relying on it even if there are shortcomings (Eisabegloo et al., 2016).

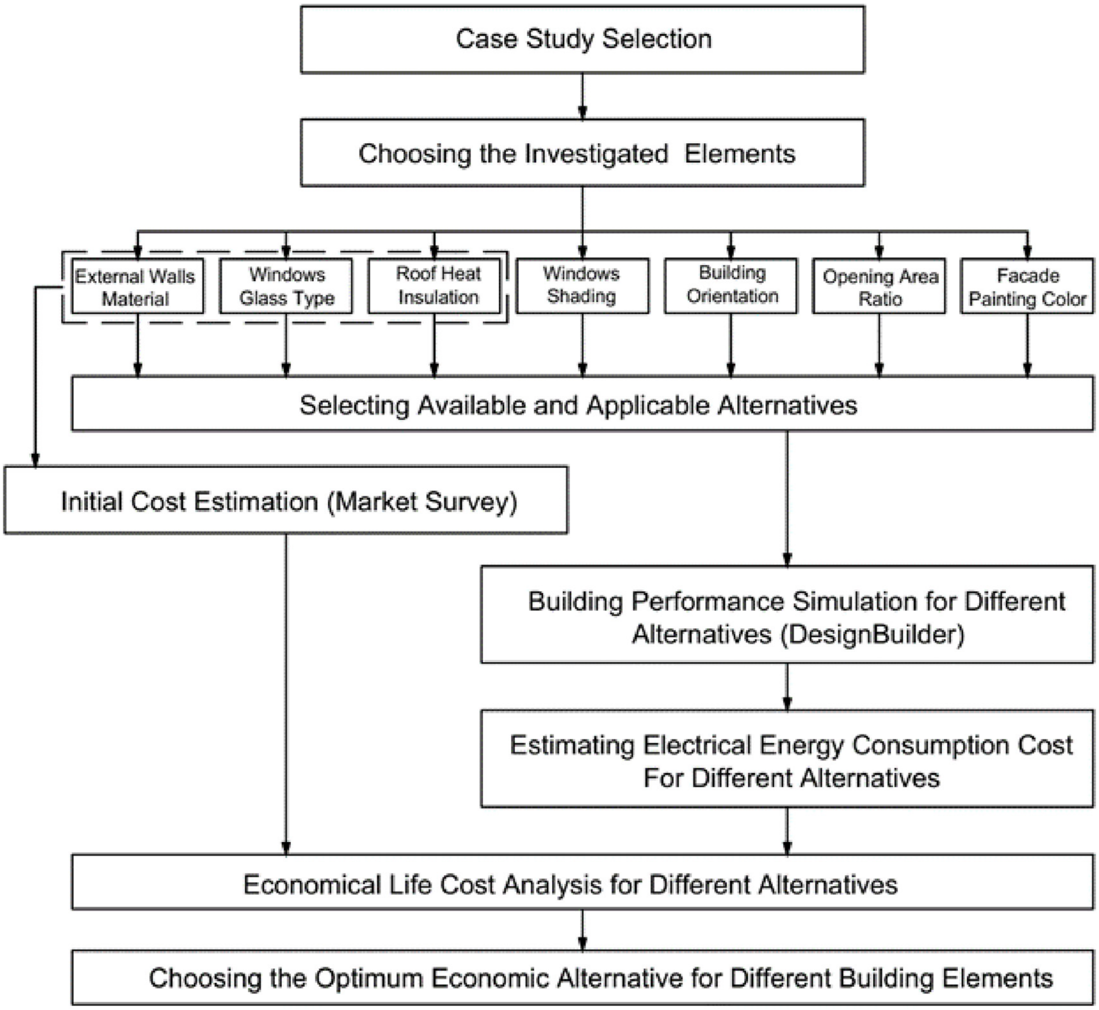
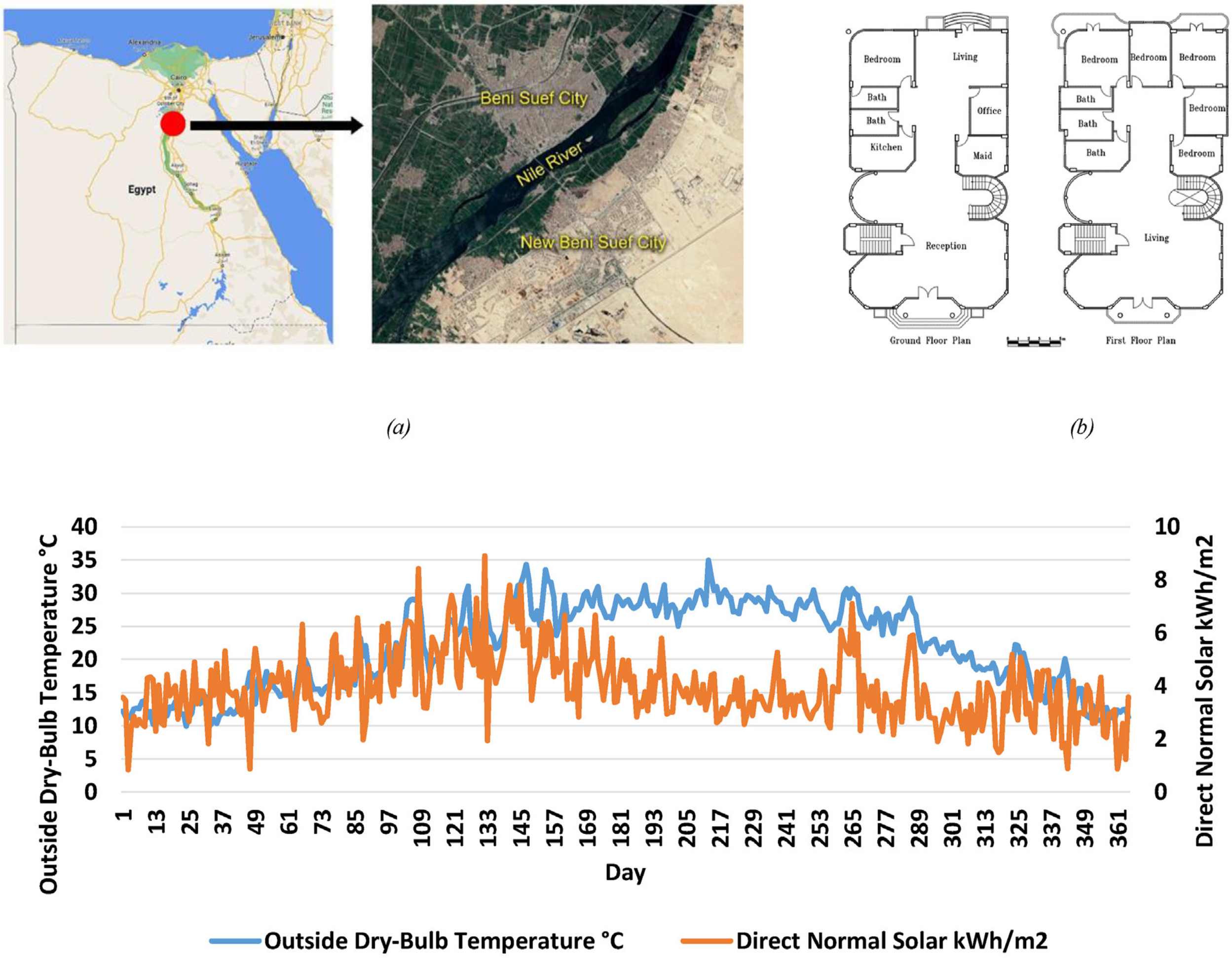


Fig. 1. Research steps.

Many International Institutions, such as the Massachusetts Institute of Technology, Stanford University, and Harvard University Graduate School of Design, trust DesignBuilder and rely on it in research and teaching, which is useful when real-world testing is impractical, expensive, or dangerous (Henry et al., 2003). Accordingly, using the DesignBuilder is consistent with the aim of the study to assess the environmental performance of different materials, which would have been challenging to implement if realistic measurements had been made. The electricity cost for each alternative will be estimated based on the energy consumption estimates. Considering the initial and estimated electricity costs, an economic cost analysis determines the most economically feasible alternative. The applied analysis compares different alternatives and evaluates their economic feasibility based on factors such as payback period, net present value, and internal rate of return. The analysis was used to identify the most economically feasible alternative to building a high-class villa in Beni-Suef, Egypt. Finally, the life cycle costs for each alternative for each element have been compared, and an optimal combination option with the lowest overall cost for each building element has been selected as an optimum alternative.

2.1. The case study

The case study for this research is a luxury villa located on Plot Number 30 in New Beni-Suef City, which is situated in the Beni-Suef Governorate in the Northern Upper Egypt Region, as illustrated in Fig. 2a. This area is known for luxury housing, entertainment, and tourism. The architectural plans are shown in Fig. 2b (New Urban Communities Authority, 2019). The reason for choosing this particular case study is that it provides a suitable example for investigating the potential of VE to



(a) (b)

(c)

Fig. 2. *(a) Case study map (b) Case study plans (c) The weather conditions for the case study.*

determine the feasibility of selecting sustainable materials in the construction industry. The villa is a high-end residential building that reflects the luxurious lifestyle of the region and the demand for high-quality construction materials and designs. By selecting this case study, the research aims to provide insights into the feasibility of choosing sustainable materials for high-end buildings, which can help promote adopting more sustainable practices in the construction industry. In addition, the villa's location in the Northern Upper Egypt Region makes it an appropriate case study as it is subject to a hot desert climate with a high solar radiation rate (Gabr, 2023). This climate poses significant challenges to building energy efficiency and makes selecting suitable construction materials and design strategies crucial. Therefore, investigating the potential of VE in determining the feasibility of choosing sustainable materials for this case study can provide valuable insights into addressing the challenges of building energy efficiency in similar climates. Also, Fig. 2c based on DesignBuilder data illustrates the average annual temperature for the selected case study, demonstrating the high-temperature conditions in the summer months.

2.2. *Choosing the instigated building elements*

The research investigates several building elements crucial to the construction industry, including the external wall material, window glass material, roof insulation, window shading, building orientation, opening area ratio, and facade paint color. These elements were chosen due to their significant impact on the building's energy performance and their potential to promote sustainability in the construction industry. The external wall material affects the building's thermal insulation and can contribute to reducing energy consumption for heating and cooling. Similarly, window glass material is crucial to the building's energy performance, as it can affect solar heat gain, daylighting, and thermal insulation. The roof insulation helps reduce heat transfer between the interior and exterior of the building, which can significantly impact the energy efficiency of the building. Window shading is essential in controlling solar heat gain and glare, which can help reduce the need for artificial lighting and cooling, contributing to energy efficiency. Building orientation is also a crucial element that can affect the building's energy performance, impacting the amount of direct sunlight and shade the building receives. The opening area ratio refers to the ratio of the window opening area to the floor area, affecting natural ventilation, thermal comfort, and energy efficiency. Finally, facade painting color can affect the building's solar reflectance and absorption, impacting the building's energy performance and ability to reduce urban heat island effects. Therefore, investigating the potential of VE to determine the feasibility of selecting sustainable materials for these building elements can provide valuable insights into promoting sustainability in the construction industry.

2.3. Choosing alternatives

The research explores several alternative materials available in the Egyptian market for each building element investigated. The alternatives were chosen based on their potential to promote sustainability and availability in the local market. Additionally, the alternatives were selected to provide a range of options for each element, allowing for a comprehensive analysis of the feasibility of selecting sustainable materials for each building element. Table 1 demonstrates the chosen materials.

3. Market survey

To determine the feasibility of selecting sustainable materials for the investigated building elements, a market survey was conducted to identify the cost of the available alternatives in the Egyptian market. The survey was conducted to estimate the costs of the items that are cost-estimable, such as the external wall material, window glass material, and roof insulation, and the other items were not included because they have not a cost or have a very low cost, which can be neglected such as (window shading). The survey was conducted based on prices available in the local market to ensure that the cost estimations are realistic and accurate for the Egyptian context.

The estimated cost for each alternative was used to estimate the overall cost for the case study, a luxury villa in New Beni-Suef City in the Northern Upper Egypt Region. By conducting this market survey and estimating the initial costs for the available alternatives, the research aims to provide valuable insights into the feasibility of selecting sustainable materials for the investigated building elements, considering the local market and cost considerations.

To determine the initial cost of implementing each item for the outer envelope. The Construction Materials Bulletin issued in February 2023 by the Ministry of Housing and Urban Utilities was relied on as a benchmark (U. and U. C. Ministry of Housing, 2023). And adjust the prices accurately according to the implementation of the construction items in Beni-Suef. The price may vary because of transportation distance differences and labor wages. A market survey was conducted for three different consulting engineers. The arithmetic average of the prices was calculated as shown in the following tables. The initial cost was calculated based on implementing each item cost per square meter, and the total item quantity cost was calculated for the first floor of the 400 m^2 case study villa. Table 2 demonstrates the materials alternatives costs.

3.1. Computational simulation

The model of the case study actual villa was created by design builder software, as shown in Fig. 3. This section aims to investigate the reduction in energy consumption by using sustainable materials in the building envelope. To achieve this goal, numerical simulations were conducted using the DesignBuilder software, one of the most reliable tools widely used in several energy-related research. The simulations will focus on the chosen building elements for investigation. The case study chosen for this simulation is a luxury villa in New Beni-Suef City, a prestigious area in the Northern Upper Egypt region used for luxury housing, entertainment, and tourism. The building's location is characterized by a hot climate for most of the year, necessitating finding architectural technologies and alternatives that reduce the building envelope's heat gain. Therefore, it is important to evaluate the energy performance of the selected building elements to identify the most effective sustainable materials and design strategies that can reduce energy consumption. DesignBuilder software is a dynamic

Table 1. The chosen materials.

Items	Description	Abbreviation
External walls	Double hollow wall: 12 cm burnt clay bricks +5 cm hollow +12 cm red bricks	EW1
	Double hollow wall: 12 cm burnt clay bricks +5 cm polystyrene +12 cm red bricks	EW2
	Double hollow wall: 12 cm burnt clay bricks +5 cm extruded polystyrene +12 cm red bricks.	EW3
	25 cm solid clay brick	EW4
	12 cm solid clay brick	EW5
	25 cm hollow clay brick	EW6
	12 cm hollow clay brick	EW7
	25 cm solid cement brick	EW8
	12 cm solid cement brick	EW9
	25 cm hollow cement brick	EW10
	12 cm hollow cement brick	EW11
Windows glass	6 mm Single clear glass	WG1
	Double Clear glass 6 mm/13 mm Air gap	WG2
	Double Clear 6 mm/13 mm Argon gap	WG3
	Single Ref-A-L Clear 6 mm	WG4
	Single Grey 6 mm	WG5
	Single Bronze 6 mm	WG6
Heat insulation	3 cm Expanded polystyrene	HI1
	5 cm Expanded polystyrene	HI2
	7 cm Expanded polystyrene	HI3
	Double roof with 5 cm heat insulation	HI4
	Double roof without heat insulation	HI5
	Green roof+5 cm heat insulation	HI6
Openings/walls area ratio	10%	WR1
	20%	WR2
	30%	WR3
	40%	WR4
	50%	WR5
Windows shading	Wooden shades	WS1
	20 cm vertical sun breakers	WS2
	40 cm vertical sun breakers	WS3
	60 cm vertical sun breakers	WS4
	20 cm horizontal sun breakers	WS5
	40 cm horizontal sun breakers	WS6
	60 cm horizontal sun breakers	WS7
	20 cm horizontal sun breakers fixed to only the southern façade	WS8
	40 cm horizontal sun breakers fixed to only the southern façade	WS9
	60 cm horizontal sun breakers fixed to only the southern façade	WS10
External Paint Colour	Light beige color	PC1
	Shiny white color	PC2
	Brick color	PC3
Building orientation	51° from north to east	BO1
	North	BO2
	West	BO3
	North	BO4
	East	BO5
	Northern east	BO6
	Southern east	BO7
	Southern west	BO8
	Northern west	BO9

Table 2. Materials alternatives cost.

	Alternatives	Quantity (square meter)	Cost per unit (EGP)	Total cost (EGP)
	External walls			
EW1	Double hollow wall: 12 cm burnt clay bricks + 5 cm hollow +12 cm red bricks	211m^2	160	33760
EW2	Double hollow wall: 12 cm burnt clay bricks + 5 cm polystyrene +12 cm red bricks	211m^2	140	29540
EW3	Double hollow wall: 12 cm burnt clay bricks + 5 cm extruded polystyrene +12 cm red bricks	211m^2	260	54860
EW4	25 cm solid clay brick	211m^2	220	46420
EW5	12 cm solid clay brick	211m^2	70	14770
EW6	25 cm hollow clay brick	211m^2	100	21100
EW7	12 cm hollow clay brick	211m^2	40	8440
EW8	25 cm solid cement brick	211m^2	440	92840
EW9	12 cm solid cement brick	211m^2	120	25320
EW10	25 cm hollow cement brick	211m^2	180	37980
EW11	12 cm hollow cement brick	211m^2	60	12660
	Windows glass			
WG1	6 mm Single clear glass	54 m^2	150	8100
WG2	Double Clear glass 6 mm/13 mm Air gap	54 m^2	950	51300
WG3	Double Clear 6 mm/13 mm Argon gap	54 m^2	1500	81000
WG4	Single Ref-A-L Clear 6 mm	54 m^2	350	18900
WG5	Single Grey 6 mm	54 m^2	400	21600
WG6	Single Bronze 6 mm	54 m^2	500	27000
	Heat insulation			
HI1	3 cm Expanded polystyrene	456 m^2	130	59280
HI2	5 cm Expanded polystyrene	456 m^2	220	100320
HI3	7 cm Expanded polystyrene	456 m^2	110	141360
HI4	Double roof with 5 cm heat insulation	456 m^2	305	139080
HI5	Double roof without heat insulation	456 m^2	85	38760
HI6	Green roof+5 cm heat insulation	456 m^2	325	148200
HI7	Green roof without heat insulation	456 m^2	105	47880

simulation tool that can calculate a wide range of thermal performance data and energy consumption for virtual building models. Using this software makes it possible to estimate the energy consumption of different alternatives for the building envelope and identify the optimal design solution that balances cost and energy efficiency. In this section, the simulation methodology and parameters used in the DesignBuilder software will be discussed in detail, and the simulation results will be presented and analyzed. The building description, occupants' number, HVAC system, and climatic input data are shown in Table 3.

4. Result and discussion

The research process culminates in presenting the findings, offering valuable insights into the feasibility of selecting sustainable materials through VE. The results are divided into three sections:

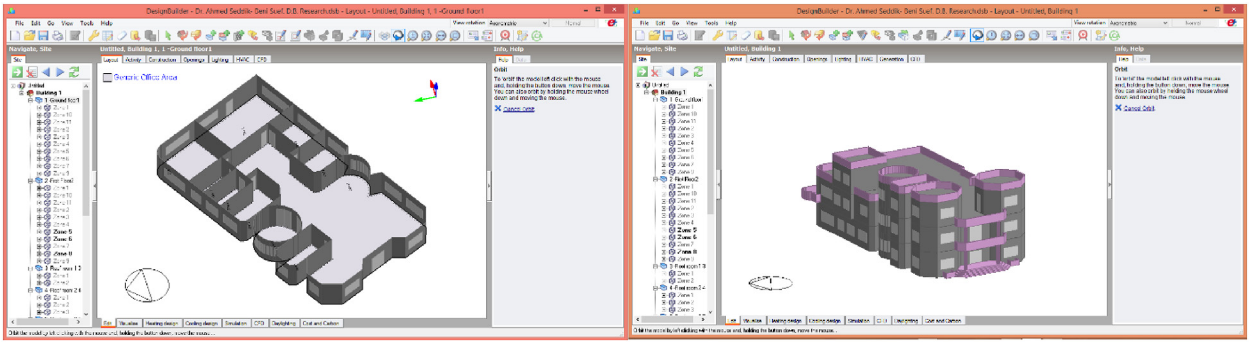


Fig. 3. The Design builder model.

Table 3. Simulation specifications.

Phases	Name	Description/Total area
Residential building description	Type of building Number of floors Total Area (Ground floor) Total Area (First floor) Total Area (Roof rooms) Gross wall area	Residential 2 (Ground floor + first floor) + Roof rooms 385.18 m^2 395.4 m^2 87.06 m^2 802.7 m^3
	Window-To-Wall Ratio (WWR)	WR1, WR2, WR3, WR4, WR5
	Types of Window Glass	WG1, WG2, WG3, WG4, WG5, WG6
	External Wall construction	EW1, EW2, EW3, EW4, EW5, EW6, EW7, EW8, EW9, EW10, EW11
	Internal Partitions construction	(inside) 2 cm thick plaster + 12 cm thick solid clay bricks + 2 cm thick plaster (inside)
	Roof construction	(outside) 1 cm thick Ceramic tiles + 2 cm thick mortar + 6 cm thick sandstone + 7 cm light concrete + 2 cm Bitumen + 15 cm concrete reinforced + 2 cm thick plaster (inside) U- VALUE = 2.322 w/m^2-k
	Roof insulation	HI1, HI2, HI3, HI4, HI5, HI6
Program Inputs	Drawing	Using drawing program window- Design Builder
	Building orientation	51.0°
	Weather Data File	Minya, Egypt
	Assuming that the building is conditioned- with refrigeration only (HVAC)	Air-conditioner Type: Split no fresh air
		Setting the Air-conditioners at a temperature of 23° Variant as shown in Figure ….
	Number of occupants	7
	Artificial Lighting	2.5 W/m3 (LED)

simulation outcomes, running cost estimations, and identifying the optimal alternative. The simulation outcomes deliver a comprehensive analysis of each alternative's energy consumption, while the running cost estimations project the total expenses for each option over 20 years. Choosing the optimal alternative ultimately relies on comparing the energy and cost analysis results. These findings illustrate the effectiveness of VE in assessing the viability of sustainable materials, serving as a crucial resource for informed decision-making in the construction industry.

4.1. Simulation results

Table 4 presents the simulation results for various building construction alternatives, including walls, windows, shading, painting, roof heat insulation, and building orientation angles. The materials alternatives are provided, with energy consumption and CO_2 emissions measured in kWh/year and kg CO_2, respectively. The U-value, indicating the wall's effectiveness in preventing heat loss, is measured in W/m^2-K. Results demonstrate that double hollow walls with polystyrene or extruded polystyrene exhibit the lowest energy consumption and CO_2 emissions.

The simulation results for different window glass alternatives measure the solar heat gain coefficient (SHGC), visible light transmittance (LT), and U-value for each option. Findings indicate that double clear glass with an air or argon gap consumes less energy than other alternatives. The simulation results for varying opening area-to-wall ratios reveal that energy consumption and CO_2 emissions increase with a higher percentage of opening area. The table also presents the simulation outcomes for different window shading alternatives, showing that wooden shades have the lowest energy consumption and CO_2 emissions.

The simulation results for various painting colors indicate that light beige color has the lowest energy consumption and CO_2 emissions. The outcomes for different roof heat insulation alternatives reveal that 7 cm expanded polystyrene has the lowest energy consumption and CO_2 emissions. The simulation results for different building orientation angles demonstrate that the orientation angles significantly impact energy consumption and CO_2 emissions, with a 51° angle from north to east yielding the lowest energy consumption and CO_2 emissions.

These simulation results can guide the selection of optimal alternatives for building construction to minimize energy consumption and CO_2 emissions.

4.2. Running cost calculations

The energy consumption cost of the outer envelope alternatives was calculated according to the incremental prices of household electricity segments announced by the Ministry of Electricity and Renewable Energy for 2022—2023. The cost of

Table 4. External walls alternatives simulation results.

ID	Alternative name	Energy Consumption (Kwh/year)	CO_2 Emissions (kg CO_2)
	External walls		
EW1	Double hollow wall: 12 cm burnt clay bricks + 5 cm hollow +12 cm red bricks	18412	13624
EW2	Double hollow wall: 12 cm burnt clay bricks + 5 cm polystyrene +12 cm red bricks	18094	13479
EW3	Double hollow wall: 12 cm burnt clay bricks + 5 cm extruded polystyrene +12 cm red bricks	18025	13246
EW4	25 cm solid clay brick	18610	13195
EW5	12 cm solid clay brick	19467	13624
EW6	25 cm hollow clay brick	18366	14251
EW7	12 cm hollow clay brick	19185	13445
EW8	25 cm solid cement brick	18862	14045
EW9	12 cm solid cement brick	19685	13808
EW10	25 cm hollow cement brick	18778	14411
EW11	12 cm hollow cement brick	19637	13747
	Windows glass		
WG1	6 mm Single clear glass	18610	13624
WG2	Double Clear glass 6 mm/13 mm Air gap	18031	13200
WG3	Double Clear 6 mm/13 mm Argon gap	18050	13214
WG4	Single Ref-A-L Clear 6 mm	15611	11428
WG5	Single Grey 6 mm	17596	12881
WG6	Single Bronze 6 mm	17678	12941
	Heat insulation		
HI0	Without thermal insulation	18610	13624
HI1	3 cm Expanded polystyrene	16470	12057
HI2	5 cm Expanded polystyrene	16121	11801
HI3	7 cm Expanded polystyrene	15932	11663
HI4	Double roof with 5 cm heat insulation	16013	11722
HI5	Double roof without heat insulation	17503	12813
HI6	Green roof+5 cm heat insulation	15920	11654
HI7	Green roof without heat insulation	18050	13214
	Openings/walls area ratio		
WR1	10%	15739	11522
WR2	20%	17140	12547
WR3	30%	18610	13624
WR4	40%	19982	14628
WR5	50%	21395	15662
	Windows shading		
WS1	Wooden shades	16337	11960
WS2	20 cm vertical sunbreakers	18278	13381
WS3	40 cm vertical sunbreakers	18050	13214
WS4	60 cm vertical sunbreakers	17898	13102
WS5	20 cm horizontal sunbreakers	18013	13187
WS6	40 cm horizontal sunbreakers	17487	12802
WS7	60 cm horizontal sunbreakers	17106	12523
WS8	20 cm horizontal sunbreakers fixed to only the southern façade	18089	13242
WS9	40 cm horizontal sunbreakers fixed to only the southern façade	17632	12908
WS10	60 cm horizontal sunbreakers fixed to only the southern façade	17301	12665
	External Paint Colour		
PC1	Light beige color	18036	13203
PC2	Shiny white color	17731	12980
PC3	Brick color	18471	13522
	Building orientation		
BO1	51° from north to east	18610	13624

(*continued on next page*)

Table 4. (continued)

ID	Alternative name	Energy Consumption (Kwh/year)	CO_2 Emissions (kg CO_2)
BO2	North	18544	13575
BO3	West	18421	13485
BO4	North	19310	14136
BO5	East	17554	12851
BO6	Northern east	18658	13659
BO7	Southern east	19393	14197
BO8	Southern west	18580	13602
BO9	Northern west	18220	13338

electricity increases as the consumption level increases, with the highest rate being EGP 1.45 per kilowatt for consumption levels above 1000 kW per month, as shown in Table 5 (El-Markaby MS, 2021). The calculations were performed based on providing subsidization for the first segments. The monthly consumption was divided according to the specified segments, and the monthly consumption value was calculated. Then, the annual total value was summed up for each alternative.

Table 5. Prices of household electricity segments.

Consumption segments kilowatt per month	EGP per kilowatt
0–50	0.48
51–100	0.58
0–200	0.77
201–350	1.06
351–650	1.28
0 < 1000	1.28
0 > 1000	1.45

Table 6. Building components alternatives running cost.

ID	Alternative name	Energy Consumption (kwh/year)	Annual Electricity Price
	External walls		
EW1	Double hollow wall: 12 cm burnt clay bricks + 5 cm hollow +12 cm red bricks	18412	26697
EW2	Double hollow wall: 12 cm burnt clay bricks + 5 cm polystyrene +12 cm red bricks	18094	26236
EW3	Double hollow wall: 12 cm burnt clay bricks + 5 cm extruded polystyrene +12 cm red bricks	18025	26136
EW4	25 cm solid clay brick	18610	26985
EW5	12 cm solid clay brick	19467	28227
EW6	25 cm hollow clay brick	18366	26631
EW7	12 cm hollow clay brick	19185	27818
EW8	25 cm solid cement brick	18862	27350
EW9	12 cm solid cement brick	19685	28543
EW10	25 cm hollow cement brick	18778	27228
EW11	12 cm hollow cement brick	19637	28474
	Windows glass		
WG1	6 mm Single clear glass	18610	26985
WG2	Double Clear glass 6 mm/13 mm Air gap	18031	26173
WG3	Double Clear 6 mm/13 mm Argon gap	18050	22636
WG4	Single Ref-A-L Clear 6 mm	15611	25514
WG5	Single Grey 6 mm	17596	25633
WG6	Single Bronze 6 mm	17678	26145
	Heat insulation		
HI1	3 cm Expanded polystyrene	16470	23882
HI2	5 cm Expanded polystyrene	16121	23375
HI3	7 cm Expanded polystyrene	15932	23101
HI4	Double roof with 5 cm heat insulation	16013	23219
HI5	Double roof without heat insulation	17503	25379
HI6	Green roof+5 cm heat insulation	15920	23084
HI7	Green roof without heat insulation	18050	26173

(*continued on next page*)

Table 6. (continued)

ID	Alternative name	Energy Consumption (kwh/year)	Annual Electricity Price
	Openings/walls area ratio		
WR1	10%	15739	22822
WR2	20%	17140	24853
WR3	30%	18610	26985
WR4	40%	19982	28974
WR5	50%	21395	31023
	windows shading		
WS1	Wooden shades	16337	23688
WS2	20 cm vertical sunbreakers	18278	26503
WS3	40 cm vertical sunbreakers	18050	26173
WS4	60 cm vertical sunbreakers	17898	25952
WS5	20 cm horizontal sunbreakers	18013	26119
WS6	40 cm horizontal sunbreakers	17487	25356
WS7	60 cm horizontal sunbreakers	17106	24804
WS8	20 cm horizontal sunbreakers fixed to only southern façade	18089	26229
WS9	40 cm horizontal sunbreakers fixed to only southern façade	17632	25566
WS10	60 cm horizontal sunbreakers fixed to only southern façade	17301	25086
	External Paint Colour		
PC1	Light beige color	18036	26152
PC2	Shiny white color	17731	25710
PC3	Brick color	18471	26783
	Building orientation		
BO1	51° from north to east	18610	26985
BO2	North	18544	26889
BO3	West	18421	26710
BO4	North	19310	28000
BO5	East	17554	25453
BO6	Northern east	18658	27054
BO7	Southern east	19393	28120
BO8	Southern west	18580	26941
BO9	Northern west	18220	26419

Table 6 presents the running costs of different building components and features based on their alternatives. These running costs are calculated in terms of the annual consumption of kilowatts and the total annual cost in EGP. For instance, it compares the running costs of different external wall alternatives, such as double hollow walls made of different materials, solid clay bricks, and solid

Table 7. Materials alternatives Return of investments periods.

ID	Alternatives Name	Total initial cost (EGP)	Annual electricity cost EGP	Life Cost Investment EGP
	External walls			
EW1	Double hollow wall: 12 cm burnt clay bricks + 5 cm hollow +12 cm red bricks	33760	26697	1368610
EW2	Double hollow wall: 12 cm burnt clay bricks + 5 cm polystyrene +12 cm red bricks	29540	26236	1341340
EW3	Double hollow wall: 12 cm burnt clay bricks + 5 cm extruded polystyrene +12 cm red bricks	54860	26136	1361660
EW4	25 cm solid clay brick	46420	26985	1395670
EW5	12 cm solid clay brick	14770	28227	1426120

(*continued on next page*)

Table 7. (continued)

ID	Alternatives Name	Total initial cost (EGP)	Annual electricity cost EGP	Life Cost Investment EGP
EW6	25 cm hollow clay brick	21100	26631	1352650
EW7	12 cm hollow clay brick	8440	27818	1399340
EW8	25 cm solid cement brick	92840	27350	1460340
EW9	12 cm solid cement brick	25320	28543	1452470
EW10	25 cm hollow cement brick	37980	27228	1399380
EW11	12 cm hollow cement brick	12660	28474	1436360
	Windows glass			
WG1	6 mm Single clear glass	8100	26985	1357350
WG2	Double Clear glass 6 mm/ 13 mm Air gap	51300	26173	1359950
WG3	Double Clear 6 mm/ 13 mm Argon gap	81000	22636	1212800
WG4	Single Ref-A-L Clear 6 mm	18900	25514	1294600
WG5	Single Grey 6 mm	21600	25633	1303250
WG6	Single Bronze 6 mm	27000	26145	1334250
	Heat insulation			
HI0	Without heat insulation	0	26985	1349250
HI1	3 cm Expanded polystyrene	59280	23882	1253380
HI2	5 cm Expanded polystyrene	100320	23375	1269070
HI3	7 cm Expanded polystyrene	141360	23101	1296410
HI4	Double roof with 5 cm heat insulation	139080	23219	1300030
HI5	Double roof without heat insulation	38760	25379	1307710
HI6	Green roof+5 cm heat insulation	148200	23084	1302400
HI7	Green roof without heat insulation	47880	26173	1356530

cement bricks. The total annual cost includes the cost of the electricity consumed by the building, which is calculated using the prices of household electricity segments.

4.3. Choosing the optimum alternative

Two methods have been employed to determine the optimal alternative from an economic standpoint. The first method involves options for which the initial cost can be calculated, allowing for calculating the life cost investment by adding the initial cost to the total energy consumption cost. The alternatives with the lowest total life cost investment are more financially viable. This method has been applied to the first three elements: walls, glass, and insulation. Table 7 presents the life cycle cost for each alternative, considering their total initial cost and total annual electricity cost. Fig. 4 compares the different alternatives based on this method and indicates the most economical option for the first three elements. For the external walls, the Double hollow wall: 12 cm burnt clay bricks +5 cm polystyrene +12 cm red bricks with ID (EW2) shows the lowest life cost investment; for the windows glass, the Double Clear 6 mm/13 mm Argon gap with ID (WG3) shows the lowest life cost investment and for heat insulation the 3 cm Expanded polystyrene with ID (HI1) shows the lowest life cost investment.

For the remaining elements, annual electricity cost savings were calculated based on Egypt's varying electricity price segments. Table 6 presents the total annual electricity cost when using each alternative. Fig. 5 compares the different alternatives and highlights the most economical option based on this method. The Figure illustrates the total estimation of the electricity cost during the life cycle of the building, and the alternatives with the lost cost were the window wall ratio 10% (WR1), the windows with wooden shades (WS1), and the shiny white color for external painting (PC2).

Consequently, Table 8 illustrates the most economically viable alternative for each element. These results emphasize the economic aspects of construction, which investors and property owners can utilize to reduce costs during the building and

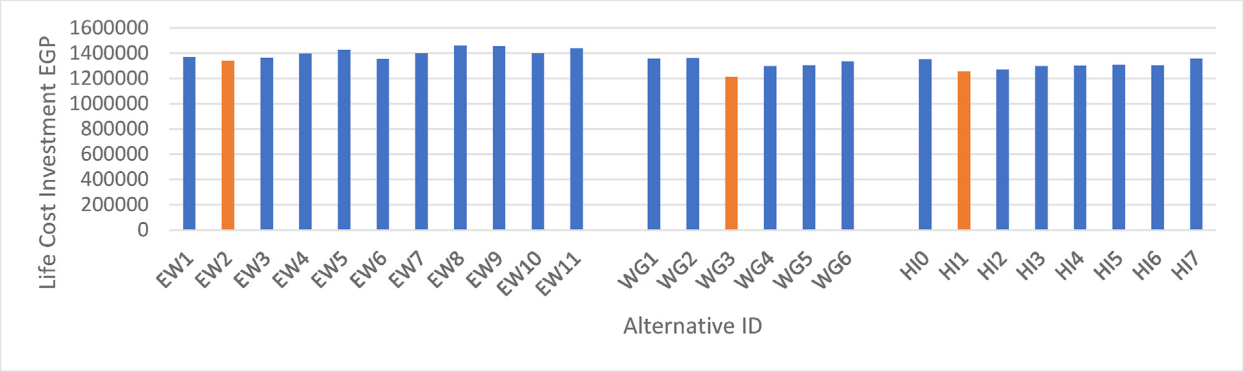


Fig. 4. Materials alternatives Return of investments periods.

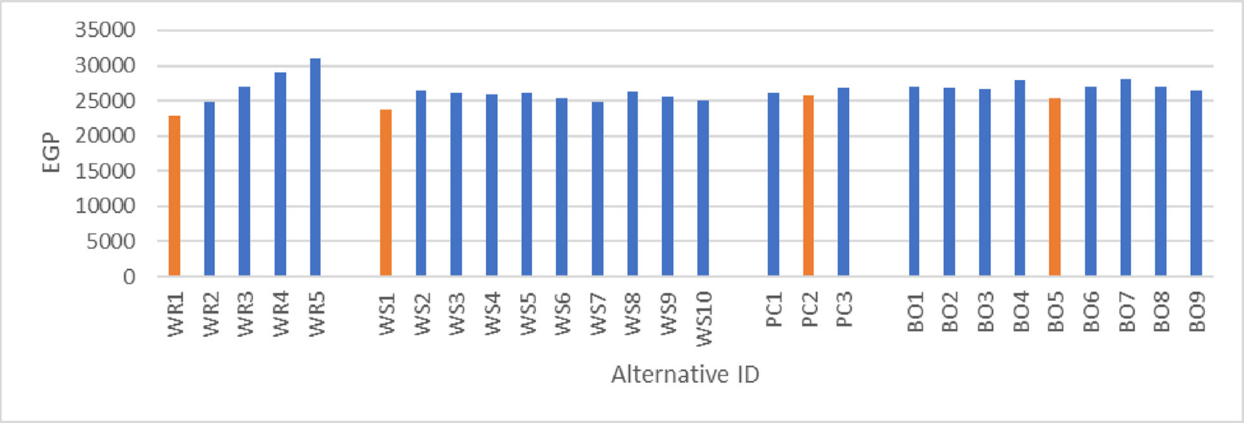


Fig. 5. Noncost elements alternatives.

Table 8. The best alternatives.

Element	Alternative ID	Alternative Name
External walls	EW2	Double hollow wall: 12 cm burnt clay bricks +5 cm polystyrene +12 cm red bricks
Windows glass	WG3	Double Clear 6 mm/ 13 mm Argon gap
Heat insulation	HI1	3 cm Expanded polystyrene
Openings/walls area ratio	WR1	10%
Windows shading	WS1	Wooden shades
External Paint Color	PC2	Shiny white color
Building orientation	PO5	East

usage phases. Moreover, these findings can be integrated with other data mentioned in the research using a multifactorial approach, considering additional factors such as environmental, aesthetic, and other considerations.

5. Conclusion

This study investigated the potential for VE to address the construction industry's economic challenges, particularly for luxury housing developments. Through critical evaluation of alternative materials and design options for various building elements, valuable insights were gained around cost-effective and sustainable solutions that bolster industry resilience during economic uncertainty. A multi-criteria analysis approach successfully determines the most cost-optimized choices for residential building elements based on lifecycle costs, energy consumption, and embodied carbon emissions. The results indicate that VE effectively balances initial investment and long-term expenditures while upholding environmental performance standards. This research emphasizes the importance of considering financial viability and sustainability criteria, especially amid growing regulatory pressures. The results provide a foundation for individual component-level evaluation that maintains designer flexibility. By independently assessing building elements and systems, designers can select optimized options without being constrained by predefined package or prototype solutions. The methodology increases the opportunity to custom-design based on budget and sustainability goals. However, it is acknowledged that the interdependencies between various building components mean their interactions must be considered to understand overall building performance. Factors like thermal bridging, indoor air quality impacts from material off-gassing, and energy flows across assemblies are examples of interdependencies that influence sustainability metrics like energy use and comfort but are challenging to capture in an isolated component study.

Several key recommendations have been proposed to advance the utilization of VE within the construction industry, particularly in luxury housing. First, Adopting VE early in the project lifecycle is crucial, emphasizing the importance of integrating it from the outset to maximize cost savings and sustainability benefits. Secondly, a collaborative decision-making approach encourages architects, engineers, and clients to work together to leverage diverse expertise in material selection and design solutions. Additionally, policy support is recommended to incentivize projects showcasing substantial energy savings and reduced carbon emissions through VE practices. Furthermore, there is a suggestion to develop specialized training programs to enhance the skills of construction industry professionals in VE applications.

Future research endeavours are proposed to deepen the understanding and application of VE in luxury housing construction. These include exploring the holistic impact of VE on building performance, encompassing aspects such as thermal comfort, air quality, and energy efficiency through comprehensive modeling and empirical studies. Long-term cost-benefit analyses are also recommended to assess the financial advantages of VE over a building's lifecycle, considering maintenance, energy consumption, and potential renovation costs. Comparative studies are proposed to quantify the benefits of VE in terms of cost savings, time efficiency, and environmental impact by comparing projects that utilized VE with those that did not. Finally, there is a call to further explore the potential of new and innovative materials and technologies to enhance the sustainability and cost-effectiveness of luxury housing projects. Through these research avenues, the application of VE can be advanced, contributing to economic resilience and sustainability within the construction industry.

Authors contribution

The First Author: Ahmed M. Seddik Hassan have made the Computational simulation.

The Second Author: Amal R. Tantawy have conducted market survey.

The Third Author: Bahaa Elboshey revised the work and shared in writing the methods, and supervision.

The last Author: Mahmoud Desouki have designed the methodology, supervised the teamwork, and wrote the literature review.

Conflicts of interest

There are no conflicts of interest.

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