ISSN No: 2456-2165
https://doi.org/10.38124/ijisrt/25jul181

Assessing the Sustainability of Residential Buildings in Kuwait Through Life Cycle Analysis

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Publication Date: 2025/07/17

Abstract: This paper presents a comprehensive environmental assessment of a residential building in Kuwait, employing a Life Cycle Assessment (LCA) approach integrated with Building Information Modelling (BIM). A detailed 3D model of a single-family villa was created in Autodesk Revit, with environmental impacts calculated using the Tally plugin, which connects BIM data to life cycle inventory datasets. The analysis covers the entire life cycle—from raw material extraction to disposal at the end of the building's 60-year lifespan—adopting a cradle-to-grave perspective. Key indicators, such as Global Warming Potential (GWP) and Primary Energy Demand (PED), were carefully examined. Results show that operational energy, especially cooling, accounts for approximately 87.4% of GWP and 91.1% of PED, highlighting the significant influence of climate and energy sources on building sustainability in hot, arid areas.

Beyond operational energy, represented emissions from construction materials—particularly concrete and steel—also play a major role in the building's overall environmental impact. Scenario analysis indicated that reducing concrete use by 30% and integrating renewable energy sources at a 50% level could reduce GWP and PED by approximately 47%. These results emphasise the importance of integrating Life Cycle Assessment (LCA) early in the design phase, along with the use of low-carbon materials and energy-efficient systems. Overall, this study supports ongoing efforts to encourage sustainable building practices in hot climates and offers a flexible, clear methodology that can be applied to future research and policy development.

Keywords: *Environmental Assessment, Residential Building, Life Cycle Assessment, Building Information Modelling, Global Warming Potential, Primary Energy Demand, Low-Carbon Materials, Energy-Efficient Systems.*

How to Cite: Saad Khalifa Rashid Al-Shahoumi; Faisal Alyamani (2025). Assessing the Sustainability of Residential Buildings in Kuwait Through Life Cycle Analysis. *International Journal of Innovative Science and Research Technology*, 10(7), 1074-1089. https://doi.org/10.38124/ijisrt/25jul181

I. INTRODUCTION

Life-Cycle Assessment (LCA) is one of the various environmental management tools companies use to measure their environmental impact. There are six life cycle stages, which include raw material extraction, manufacturing, construction, operation of the building, demolition, and reuse or recycling [1]. All building development life stages require a strong utilisation of natural resources and power supplies. At each building life stage, energy performs the following functions: extracting materials, manufacturing materials, assembling components, operating the building for people's use, tearing down the building, and disposing of rubble off-site [2].

Buildings create many environmental problems because they exist through multiple stages over many years. During the building life cycle, natural resources, energy, and water are used, which leads to the production of greenhouse gases and pollutants at each stage [3]. The first stage is the manufacturing stage, in which raw materials are converted into building materials, such as steel, concrete, and plastic. Producing construction materials requires a significant amount of energy and primarily relies on fossil fuels, which generate substantial amounts of harmful greenhouse gases. The cement sector by itself creates 5% of Earth's carbon pollution. The process of making construction materials creates pollution and generates large amounts of waste that damages our natural environment [4]. For example, South Africa requires 7 metric tonnes of raw materials annually for concrete, cement and aggregate

ISSN No: 2456-2165 https://doi.org/10.38124/ijisrt/25jul181

production, while generating 4.92 × 10^9 kg of CO2 in annual emissions [5].

The construction phase involves transporting building materials to the site, where assembly work is performed to create a new structure. A mass of materials, along with an energy drain, arises from the use of machinery tools during this stage. Waste material management during construction, along with heavy truck transportation operations, enhances both fossil fuel usage and pollution emissions [6]. Buildings maintain their operational and use phase until the end of their full lifespan. During this period, buildings require water and energy resources to operate their heating and cooling systems and meet the lighting needs of daily activities. During this period, essential facilities manage responsibilities for water distribution and sewage waste management [7].

When a building fulfils its intended purpose, its demolition phase begins and involves taking the structure apart while handling the generated waste. The demolition methods require substantial fossil fuel energy use, which results in high emission levels for the environment. Building demolition approaches which enable material recovery create positive environmental effects by minimising waste sent to landfills [8].

The rapid rise in residential construction in Kuwait results in substantial resource usage, generates waste products, and produces CO2 emissions. Two sectors that directly influence each other are strengthening their operations to respond to increased demands for building and construction. The residential sector represents one of the most valuable building areas [9]

The development cycle, comprising construction, operation, and demolition, consumes important environmental resources. Buildings constructed traditionally reduce substantial amounts of energy resources, along with water and raw materials [10].

This research employs Revit 3D Modelling, as well as the Tally Plugin, to examine environmental effects throughout the residential construction stages in Kuwait. The analysis also determines which material produces the greatest negative impact on the environmental performance of buildings.

Environmental concerns at both local and global scales continue to grow throughout the worldwide community. By 2040, the construction sector is projected to account for 21% of global energy consumption, while using 32% of the energy required for building operations. The construction of 60% of the future infrastructure required by 2050 will lead to a significant increase in planetary resource usage. Buildings represent an exceptional opportunity to reduce GHG emissions during the next few years. Buildings offer substantial opportunities to reduce GHG emissions over a short time frame [11]. LCA serves as a standard methodology across diverse international locations to investigate cost performance and environmental aspects of building constructions. Measuring buildings' sustainability performance requires sustainability indicators which establish performance standards.

II. LITERATURE REVIEW

Life Cycle Assessment (LCA) is a critical tool used to evaluate the environmental impacts of buildings throughout their life cycle stages: raw material extraction, manufacturing, construction, operation, demolition, and recycling. Each stage involves significant consumption of natural resources and energy, leading to environmental degradation [12].

Recent research has focused on LCA's role within the construction industry for the identification and mitigation of environmental effects. For example, [13] has discussed methodologies and applications related to LCA in construction materials, emphasising the importance of making sustainable decisions. Similarly, [14] discusses the possibility of using fibreglass as an environmentally friendly building material in Kuwait and shows how LCA can inform decisions related to the choice of environmentally friendly materials. These studies emphasise the significance of LCA in achieving sustainability and reducing the ecological footprint within construction activities.

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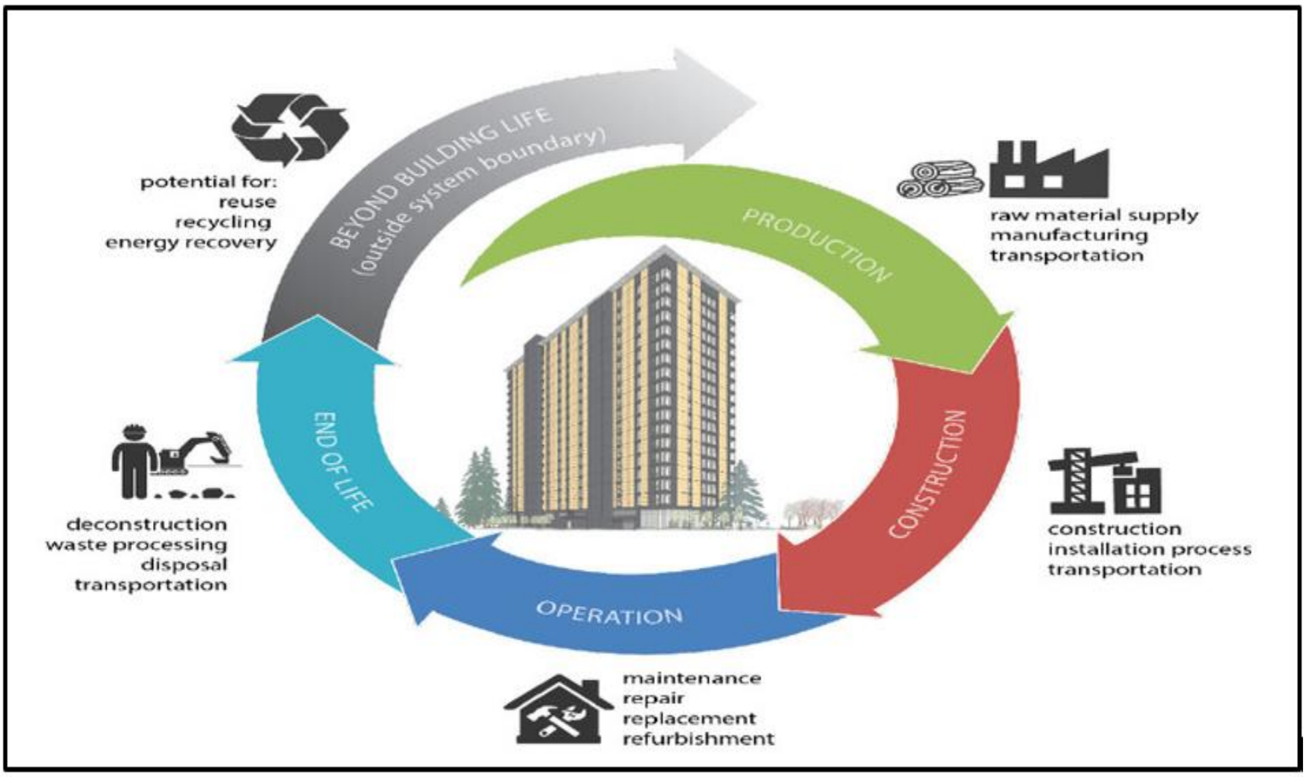

Fig 1 Life Cycle Assessment (LCA) phases

➢ *Environmental Impact of Building Materials in Kuwait*

The environmental impact of building materials is a critical issue related to fast urbanisation and the construction boom in Kuwait. The production and use of the main construction materials, such as concrete and steel, are remarkably energy-intensive and heavily contribute to GHG emissions [15]. The cement industry is among the leading causes of CO2 emissions in Kuwait. This can be attributed to the fact that energy from fossil fuels has traditionally been relied upon during production.

Additionally, the production of building materials is quite wasteful and polluting, posing destructive effects on the local environment [16]. Building in Kuwait is reported to consume approximately 70% of the nation's energy supply, which increases yearly by 8% [14]. So, the rapid increase in residential buildings in Kuwait has resulted in great consumption of resources, waste generation, and CO2 emissions. Construction, operation, and demolition processes involved in a building's lifecycle consume a significant amount of natural resources and generate substantial waste and greenhouse gases. It is, therefore, very important that the building sector be made sustainable through the adoption of green building concepts [17].

➢ *Phases of the Building Life Cycle*

- *Construction Phase*

At the construction stage, the material is transported to the site and assembled, requiring large quantities of energy and generating substantial waste. Additionally, the transport of materials contributes to the use and emission of fossil fuels. This stage is particularly critical, as it involves the use of heavy machines and equipment, which are major sources of energy consumption and emissions. The environmental impact during this phase can be reduced by the adoption of sustainable construction practices and the use of eco-friendly materials [13]. For instance, the manufacturing of concrete in Kuwait generates approximately 470-530 kg of CO_2 per cubic meter of concrete [18]. This high level of emissions is primarily due to the energy-intensive processes involved in cement production and water desalination.

- *Operation and Use Phase*

The operation and use phase encompasses energy and water consumption during daily activities throughout the entire lifetime of a building, which is typically more than 50 years. Most buildings are dependent on energy coming from fossil-fuel-based resources, which leads to greenhouse gas emissions. This phase is considered important because most of the energy consumption of a building and its environmental effects fall under this category. In this phase, a significant reduction in environmental footprint may be achieved by the implementation of energy-efficient systems and renewable sources of energy [19].

Buildings in Kuwait are considered among the main consumers of energy. The consumption of energy is highly dominated by air conditioning. In a study carried out by [19], it was remarked that air conditioning occupies about 70% of the total energy use in residential buildings. Extreme temperatures in Kuwait drive such high energy use; during summer, the temperature can reach over 50°C. In the case of residential buildings, heavy dependence on fossil fuel-based energy has resulted in significant greenhouse gas emissions. The energy and exergy efficiencies were estimated at 80.99%

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and 6.37%, respectively, for the residential sector by [20], while huge losses were recorded for air conditioning systems. This has resulted in a high amount of CO_2 emissions from this sector and contributes a great deal to the overall carbon footprint in Kuwait.

- *Maintenance and Repair*

Maintenance activities, necessary to keep the buildings functional, require more material and energy use, produce waste, and repeat the earlier environmental impacts. Routine maintenance is quite important for the longevity and performance of buildings; at the same time, it contributes to the overall environmental impact. In this respect, sustainable maintenance means using durable materials and efficient techniques for repairs that can minimise such impacts [21].

- *Demolition and Recycling*

It faces demolition at the end of a building's life, a process which produces quite a lot of waste. Good demolition practice should, therefore, be used to recover the materials for recycling, hence causing minimal environmental degradation. Recycling and re-use of materials such as concrete and steel make for a circular economy; sustainability is achieved. Recent research has highlighted the potential of recycling and reusing building materials to reduce waste and conserve natural resources [14].

➢ *Comparative Analysis of LCA Methodologies*

LCA methodologies differ significantly from one region to another and from application to application, since results and interpretations of environmental impacts vary. Of the various primary factors of variation, the definition of system boundaries is at the top. In different LCA studies, the system boundary definitions differ, which may affect the scope of the assessment [22]. For instance, some studies consider only the construction phase, while others may consider the whole life cycle, starting from the extraction of raw materials to demolition [23].

Furthermore, different methodologies also represent impact categories in varying choices. The chosen impact categories might include global warming potential, ozone depletion, and acidification. A selection has to be made of what matters with regard to overall environmental impact assessment and comparability [24]. Also, data quality and sources will vary from one LCA study to another. Some methodologies are based on primary data from specific projects, while others draw on secondary data from databases. The accuracy of the results is related directly to the quality of the data [23].

Another important factor is geographical variations in LCA methodologies. Because of geographical regions' different environmental regulations, construction practices, and resource availability, LCA methodologies can be different. For example, the standards of European LCA may vary from North American or Asian ones [23]. Several software tools are also available for conducting LCA, such as Tally Plugin, SimaPro, GaBi, and One Click LCA. Besides, various tools exhibit different features, databases, and methods of calculation, and these might be a reason for the dissimilarity in the results.

Tally is a premium add-in in Autodesk Revit and brings Life Cycle Assessment (LCA) embedded in Building Information Modelling (BIM) [25]. Tally makes considerations of environmental consequences from building material inputs through successive stages of residential construction at a live level for both architects and engineers [26]. Users have the capability of carrying out an integrated environmental analysis using Tally inside of Revit that will quantify all of the life-stage, embodied consequences of materials to the systems: land, air, and water [27]. This will be really helpful for countries like Kuwait, which are facing a very rapid process of urbanisation and definitely need buildings that could be more sustainable. Tally offers a very massive database with extensive information on nearly all types of construction materials, enabling users to comparatively analyse them and then choose those with the highest potential environmental impacts [28]. Such insight allows for informed decision-making by promoting eco-friendly material selections and design options that enhance residential building sustainability. It will also help professionals to reduce environmental impact by applying Tally, thus creating better sustainability in the building construction process.

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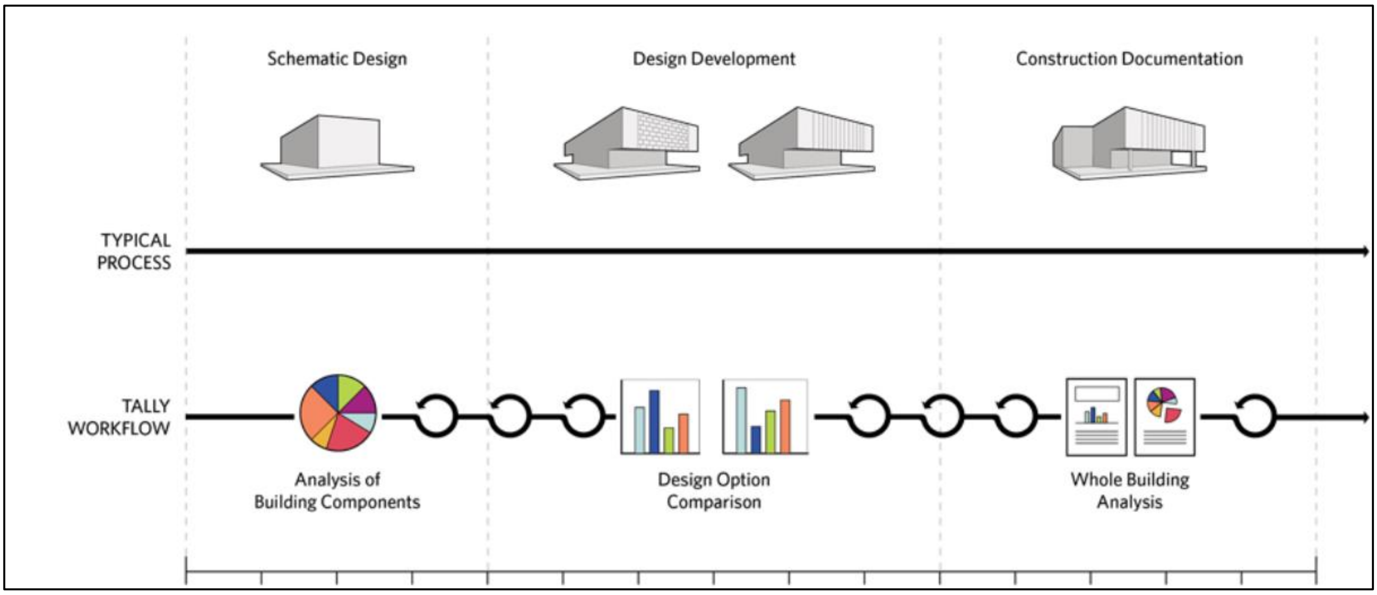

Fig 2 Environmental Impact Assessment Using Tally Plugin in Autodesk Revit

➢ *Case Studies on LCA in Residential Buildings in Kuwait*

Al-Sammar and Aleis [14] conducted an environmental comparative study of FG rooms versus AAC rooms at the Kuwait Institute for Scientific Research in the year 2023. The research evaluated the environmental impacts from construction to operation, with particular emphasis on AC, which accounts for more than 70% of electricity consumption in Kuwait during summer. It assessed CCHH, OD, FD, and MD as some of the environmental impact categories during the construction phase of the study. The construction of FG rooms had the potential to reduce energy consumption and environmental impacts compared to AAC rooms. In the operational stage, the energy consumption of AC in the FG and AAC rooms is estimated to be 8174.7 kWh and 5274 kWh annually, respectively. The study pointed out that the highest environmental impact in both scenarios was due to electricity used for AC; this again emphasised the need for energy-efficient building materials and systems [14].

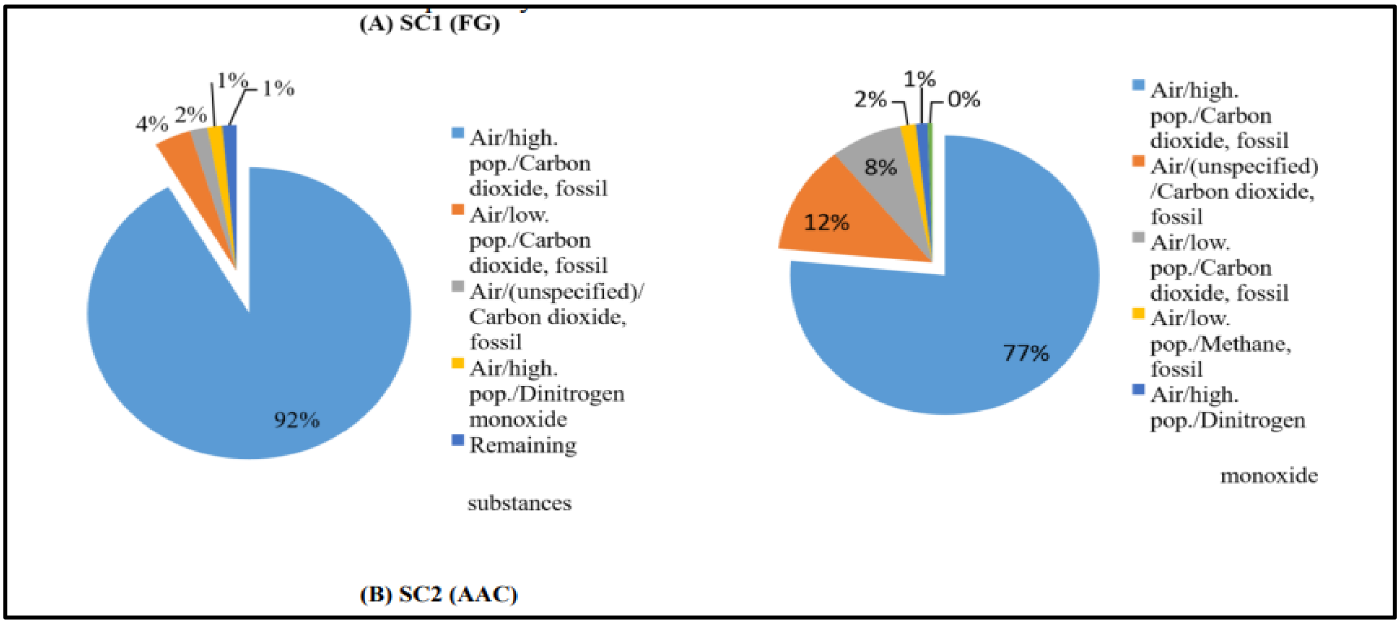

Fig 3 Element Contribution to Climate Change Human Health (CCHH) for SC1 (Fibreglass) and SC2 (Autoclaved Aerated Concrete) [14]

Figure 3 presents the impact of several factors on the CCHH category for two scenarios, SC1 (Fiberglass, FG) and SC2 (Autoclaved Aerated Concrete, AAC), and how each of these materials contributes to climate change with respect to human health, thus helping identify which has the higher negative environmental impact [14].

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Another study investigates the concept of energy-autonomous buildings in Kuwait, aiming at their sustainable design and integration with renewable technologies. Autonomous Buildings have the potential to achieve energy self-sufficiency, zero grid connection, zero carbon emissions, and energy bills. A pioneering example of Autonomous Building in Kuwait was highlighted in the paper, provided with roof-mounted solar panels [29]. Detailed climate and local construction research have led to the development of innovative housing and transportation solutions with a 100% green energy supply and demand. The emphasis of this study is that integrated renewable technologies can be combined with new approaches in a hot, arid climate to meet energy needs. The results prove the viability and economic viability of Autonomous Buildings, taking offset costs into account. It also highlights the role of Autonomous Buildings in decarbonisation, digitalisation, decentralisation, and democratisation of energy, underscoring the importance of green cooling, heating, and electricity in reducing CO2 emissions [29].

III. METHODOLOGY

A simulation-based environmental assessment was employed to evaluate the environmental performance of a residential building in Kuwait. The study was framed based on the integration of Building Information Modelling (BIM) and Life Cycle Assessment (LCA) tools. A cradle-to-grave system boundary was adopted to cover all life cycle stages—from raw material extraction to end-of-life-to be considered in the analysis. The method was designed to comply with ISO 14040 and ISO 14044 standards for LCA.

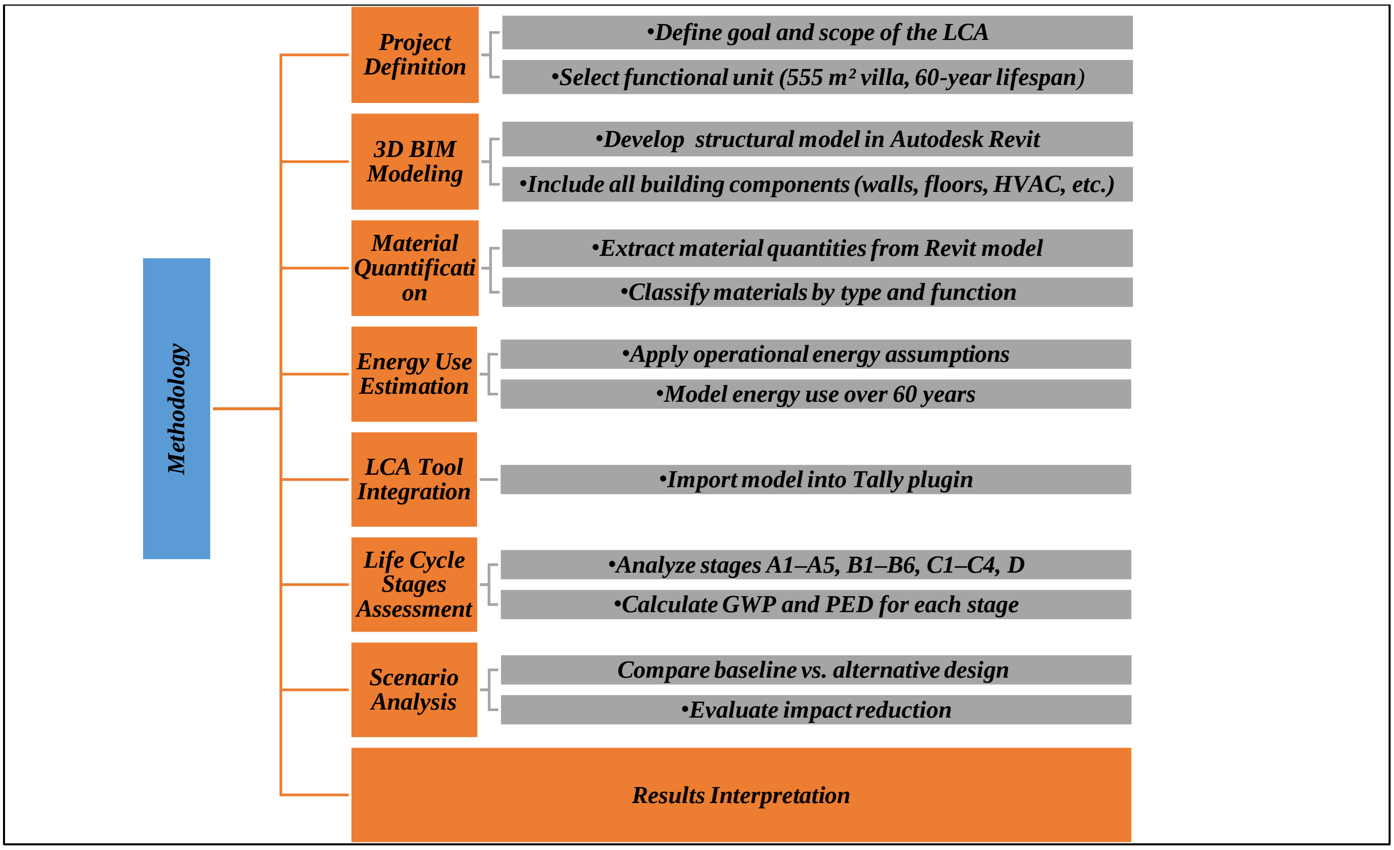

Fig 4 Flow Diagram Structure for Methodology

➢ *Development of BIM Model*

A detailed 3D model of a single-family villa was developed using Autodesk Revit. The model consisted of architectural, structural, and mechanical components, including walls, floors, roofs, columns, and HVAC systems. Parametric modelling features in Revit were employed to determine volumes of materials and spatial configurations, which were then used as inputs for the LCA. The model was designed to reflect traditional Kuwait residential building practice.

Figure 4 presents a three-dimensional (3D) architectural model of the villa. The structure consists of a basement, ground, first and roof floors and includes clearly defined structural elements such as columns, beams, and floor slabs. The total area of the villa is 555 m².

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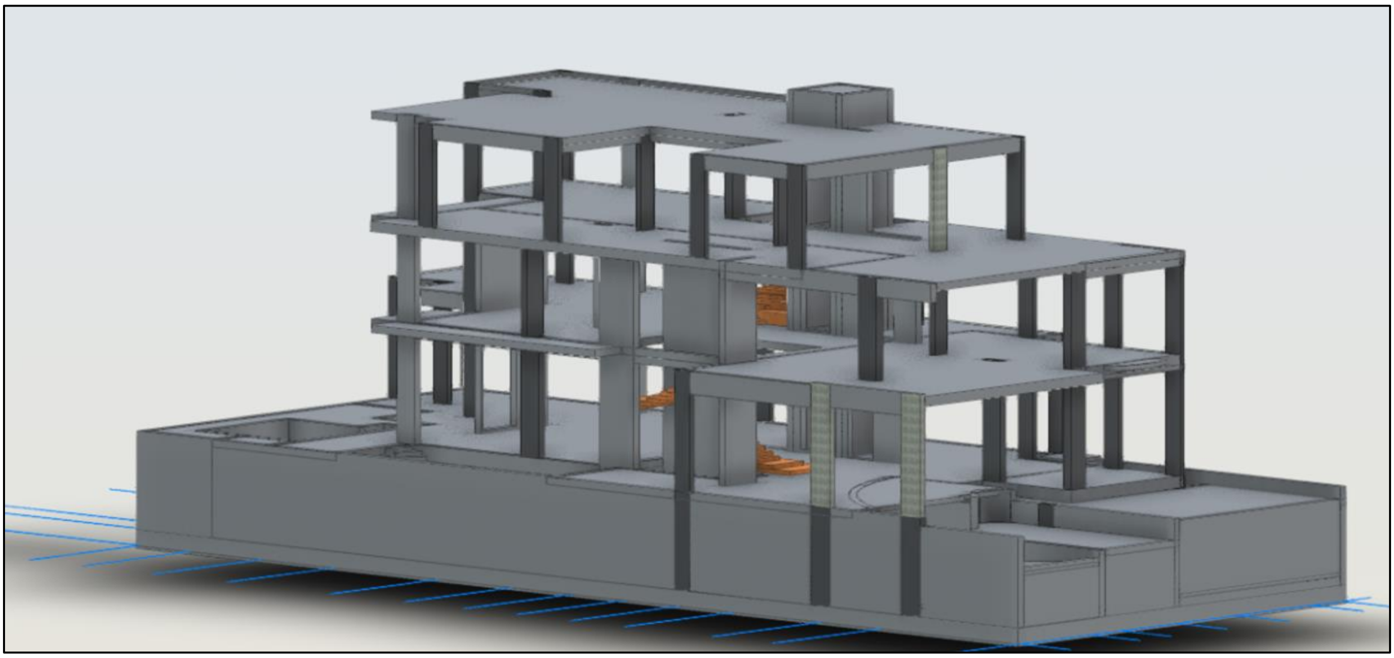

Fig 5 3D View of the Concrete Structural Villa

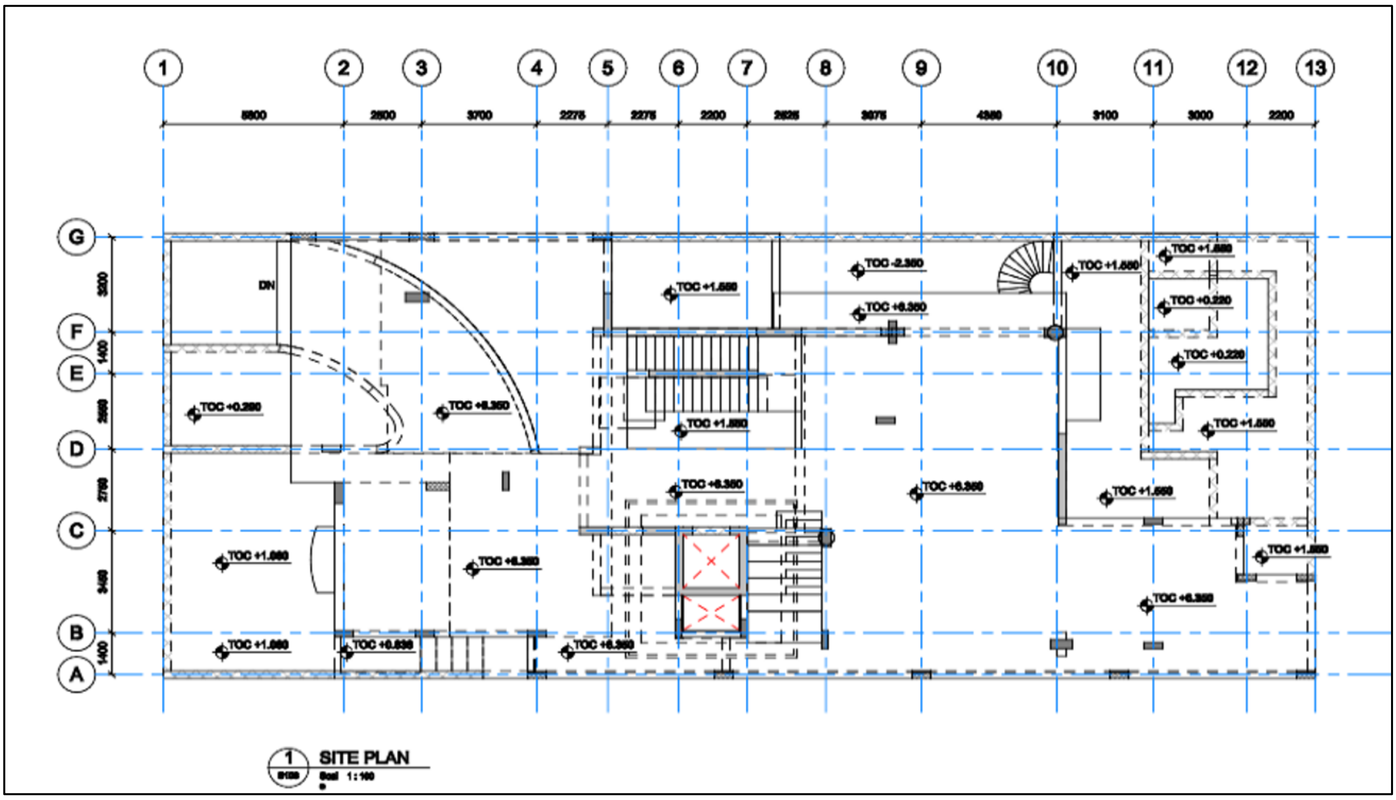

Fig 6 Site Plan of the Concrete Structure Villa

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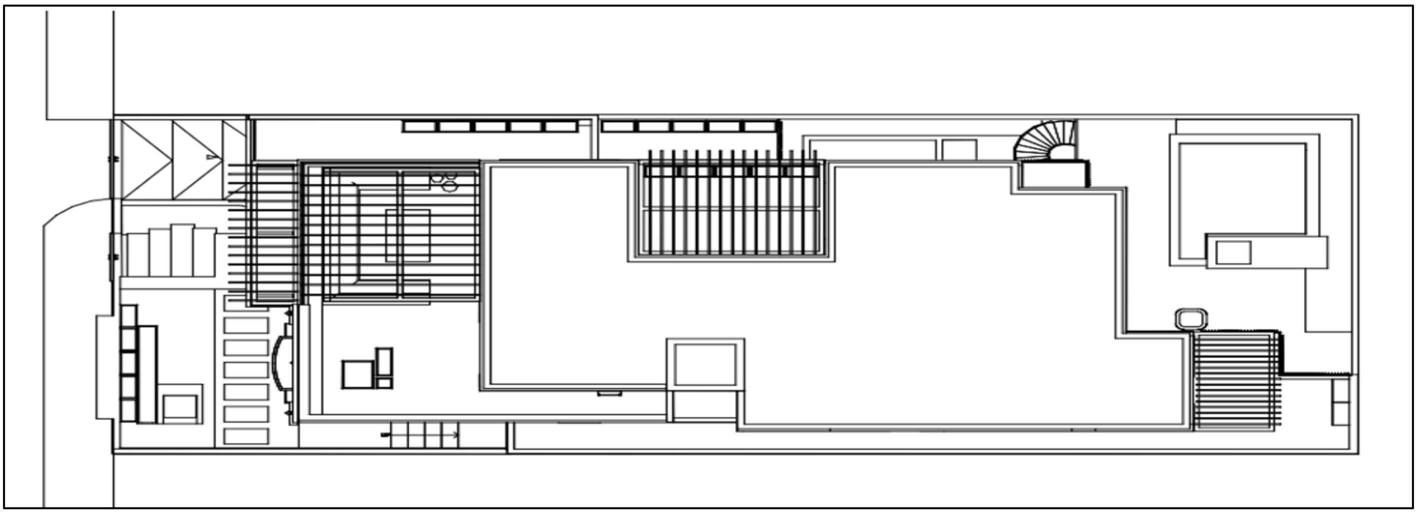

Fig 7 Key Plan of the Project

➢ *Estimation of Energy Use*

Operational energy consumption was calculated from average residential consumption levels in Kuwait. Yearly electricity consumption was assumed to be 216.22 kWh/m², and heating energy was assumed to be 108.11 kWh/m². These values were assumed over a 60-year building life to consider the long-term environmental impacts. The assumptions were based on local climate and the average performance of HVAC systems.

➢ *Tool Selection and Integration*

The Tally plugin, embedded within Autodesk Revit, was used to conduct the LCA. The environmental effect data were obtained from Tally's life cycle inventory (LCI) database based on GaBi datasets. The plugin supported the computation of important indicators, such as Global Warming Potential (GWP) and Primary Energy Demand (PED), as well as other environmental metrics. The embedding of Tally within Revit supported real-time evaluation of environmental effects in accordance with the material specifications in the model.

➢ *System Boundary and Functional Unit*

The LCA was performed for the cradle-to-grave system boundary and included the following phases:

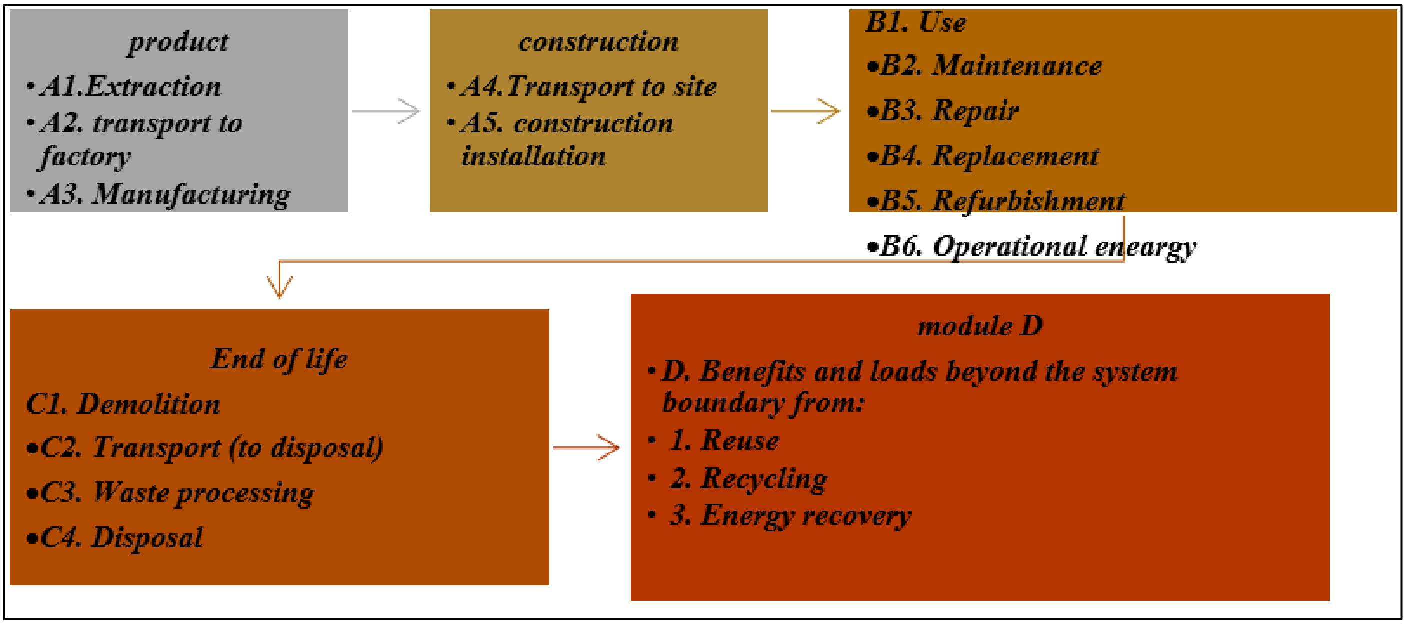

Fig 8 Life-Cycle Stages As Defined By EN 15978. Processes Included In Tally Modelling.

IV. RESULTS AND DISCUSSION

This study performs a whole-building Life Cycle Assessment (LCA) on a simulated Kuwaiti single-family villa model in Autodesk Revit, evaluating it using the Tally plugin. The study takes into account the entire building life cycle, from raw material extraction to end-of-life disposal, over a 60-year building operating life. The environmental effects are quantified under several categories with a focus on Global Warming Potential (GWP) and Primary Energy Demand (PED), the main drivers of climate change and resource depletion.

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The building's total GWP is 7,988,173 kg CO_2eq, and PED is 117,625,020 MJ. These are the summation of the building's environmental burden from materials, construction, operation, and end-of-life disposal. Most importantly, the Operational Energy phase (B6) alone contributes 6,980,810 kg CO_2eq and 107,209,876 MJ, accounting for 87.4% of the total GWP and 91.1% of the total PED, respectively. This is owing to the fact that the villa is located in a warm climate with high cooling needs, and electricity generation is mostly fossil-based.

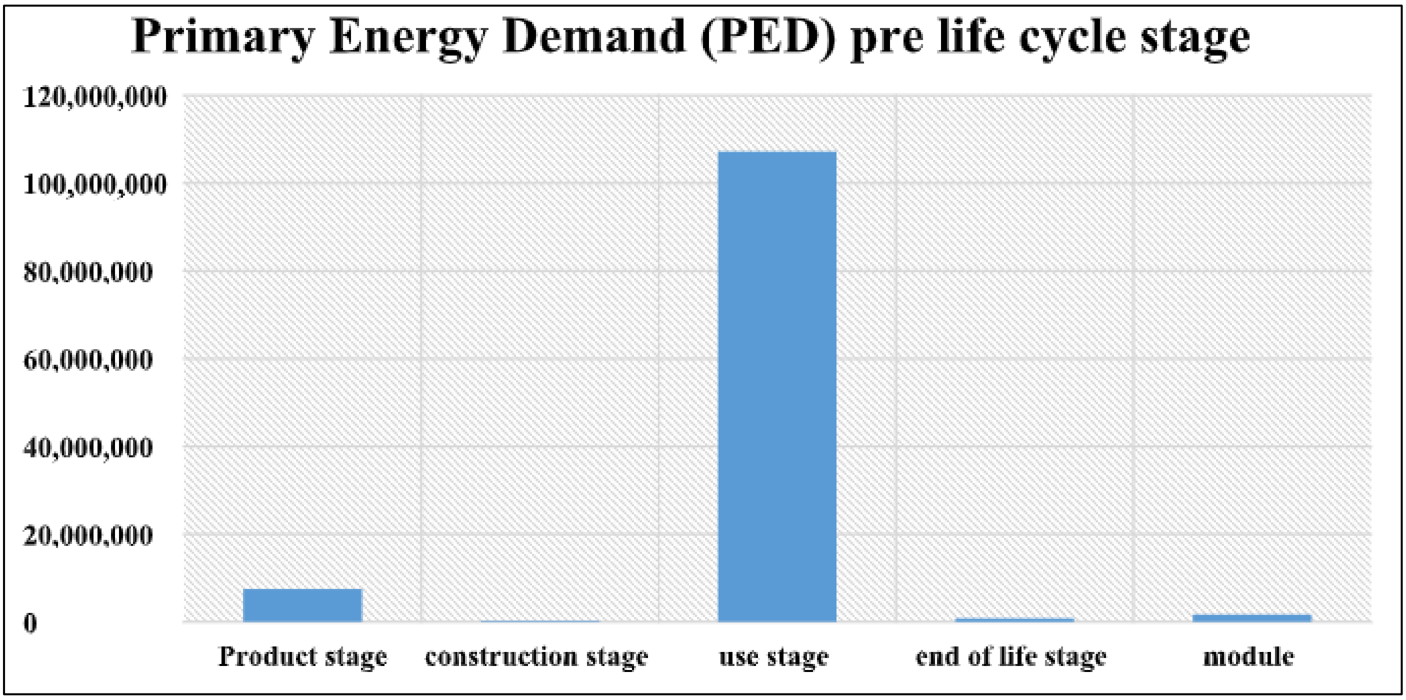

Fig 9 Results per Life Cycle Stage

These findings are in agreement with recent studies in hot-humid climates, the Middle East and the U.S. Gulf Coast, where operational energy always outweighs embodied impacts. HVAC systems in hot climates have unbalanced life cycle emissions, especially when powered by carbon-emitting grids, and buildings in arid climates require both passive and active measures to reduce cooling loads and GHG emissions [30].

To provide for this, the operational energy used was modelled for the villa founded upon annual electricity use of 216.22 kWh/m² and heating energy use of 108.11 kWh/m² over an area of 555 m² gross for 60 years. These totals give more than 107 million MJ of energy used in operation and thus further confirm the critical need for energy-efficient design in this kind of climatic context.

➢ *Environmental Impact by Life Cycle Stage*

The results evidently show that the Use Stage (B6) is the most energy and emission-demanding. This aligns with the conclusions of Monnier et al. (2024), who have integrated overheating risks into LCA models and accounted for operational energy in warm climates to contribute over 80% of overall life cycle impacts [31].

Table 1 Environmental Impact by Life Cycle Stage

Life Cycle Stage	GWP (kg CO_2eq)	PED (MJ)	GWP (%)	PED (%)
A1–A3 Product	684,205	7,484,372	8.6	6.4
A4 Transportation	12,370	179,880	0.15	0.15
A5 On-site Construction	4,473	67,401	0.06	0.06
B2–B5 Maintenance	0	0	0.00	0.00
B6 Operational Energy	6,980,810	107,209,876	87.4	91.1
C2–C4 End of Life	103,441	914,948	1.3	0.8
D Module D (Recycling)	202,875	1,768,544	2.5	1.5
Total	7,988,173	117,625,020	100	100

$$\mathbf{GWP}\ (\%) = \frac{\boldsymbol{GWP\ of\ Product\ stage\ (A1-A3)}}{\mathbf{Total\ GWP}} = \frac{684{,}205}{7{,}988{,}173} = \mathbf{8.6}\%$$

$$\mathbf{PED}\ (\%) = \frac{\boldsymbol{PED\ of\ Product\ stage\ (A1-A3)}}{\mathbf{Total\ PED}} = \frac{7484372}{117625020} = \mathbf{6.4}\%$$

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The Product Stage (A1–A3) of material production and manufacturing contributes 8.6% of GWP and 6.4% of PED. This is mostly due to the usage of concrete and steel, since both have large amounts of embodied carbon. The Tally report confirms structural concrete (3000 psi, 30% fly ash) and reinforcing steel as the most critical materials, contributing over 1 million kg CO_2eq combined.

Transport (A4), construction (A5), and end-of-life (C2–C4) stages produce proportionally small quantities, a total of 1% GWP and below 2% PED. Module D, recycling and energy recovery, also provides little environmental benefit, reducing the net effect by 202,875 kg CO_2eq and 1.77 million MJ.

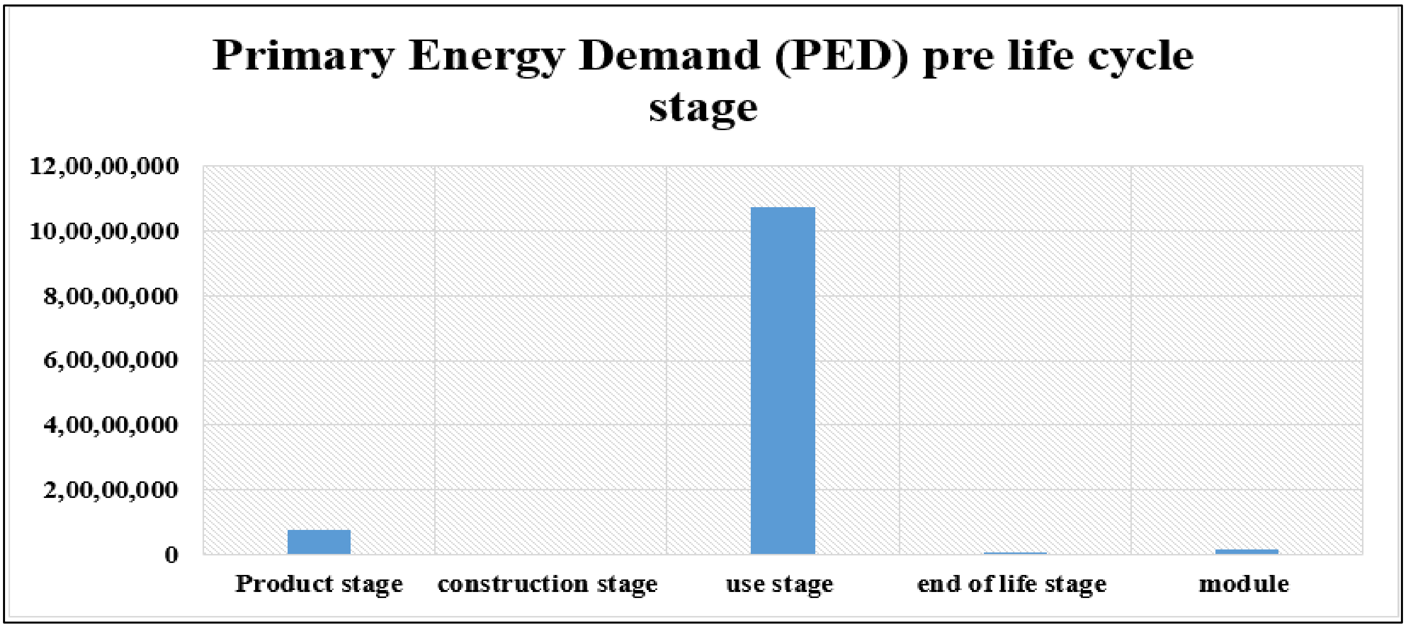

Fig 11 Primary Energy Demand (PED) Pre-Life Cycle Stage

- *Material Contributions to Environmental Impact*

The sustainability of construction materials is a hot issue when it comes to the construction of sustainable buildings. With the Kuwait VILLA project, Tally, coupled with Autodesk Revit, was used to perform Life Cycle Assessment (LCA) of the environmental burdens of each of the materials. This section has two indicators considered, i. e. Global Warming Potential (GWP) and Primary Energy Demand (PED). Table 2 summarises the global warming potential (GWP) and primary energy demand (PED) for the key materials used in the Kuwait villa project.

Table 2 GWP and PED for the Key Materials.

Material	GWP (kg CO_2eq)	PED (MJ)
03 - Concrete	1,002,889.74	10,347,743.54
Steel, concrete reinforcing steel, CMC - EPD	577,993.25	6,649,568.90
Structural concrete, 3000 psi, 30% fly ash	424,896.49	3,698,174.64
Construction Electricity	4,305.00	65,000.00
Construction Heating	108.54	1,890.00
Construction Water	59.4	510.6
Operational Electricity	6,199,308.49	93,601,638.00

- *Global Warming Potential (GWP)*

GWP is representing the total amount of greenhouse gases in kilograms of CO 2 equivalent (kgCO 2eq). It is a representation of the contribution of the material to climate change in the life cycle. It was analysed that the highest was concrete (03 - Concrete) with more than 1,002,889 kgCO2 eq, owing to its large amount and energy consuming production process. Steel reinforcement (CMC - EPD) came second at 577,993 kg CO2eq, despite having a lower mass, indicating a high emission intensity per kilogram. The use of supplementary cementitious materials was evidenced where structural concrete made up of 30 percent fly ash reduced GWP (424,896 kgCO2 eq). These results further demonstrate the importance of material selection in reducing embodied carbon. Lacing concrete mixtures with fly ash contributes hugely to emissions out of the fact that Portland cement, which is the main contributor of CO2, is completely or partly replaced by the fly ash.

- *Primary Energy Demand (PED)*

PED measures the amount of energy needed in the life cycle of the material, which is the extraction of the material,

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processing, transportation and installation. The findings revealed that concrete prevailed again with a PED of 10.3 million MJ, as it is extensively used and has an energy-intensive production process. Steel reinforcement required 6.6 million MJ, underscoring its significant environmental impact. Structural concrete made with fly ash required 3.7 million Mj, further contributing to the fact that it is used in energy-efficient buildings. These numbers highlight a two-fold problem with concrete and steel: on the one hand, these materials are vital to structural integrity; on the other hand, they remain the most environmentally demanding materials. It is essential to decrease their consumption or start using alternatives with less impact to practice sustainable development.

The comparative impacts are better illustrated in Figure 1, which provides a bar chart representation of the GWP and PED of major materials.

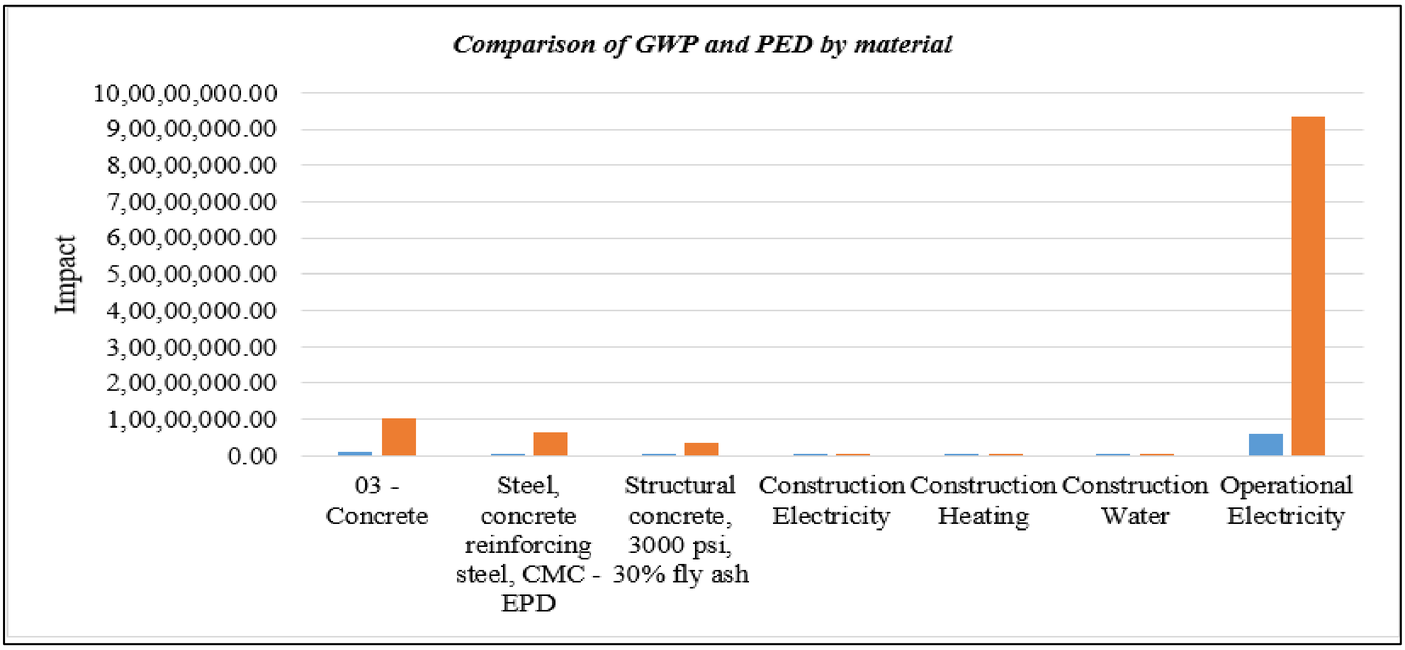

Fig 10 GWP and PED Comparison by Material.

This visualisation tells it all, as concrete and steel carry disproportionately environmentally costly loads, which further justifies strategic material minimisation in the design stage.

➢ *Elemental Impact Distribution*

The Tally report of the environmental assessment shows an evident distribution of discharges on different elements of a building modelled in Revit.

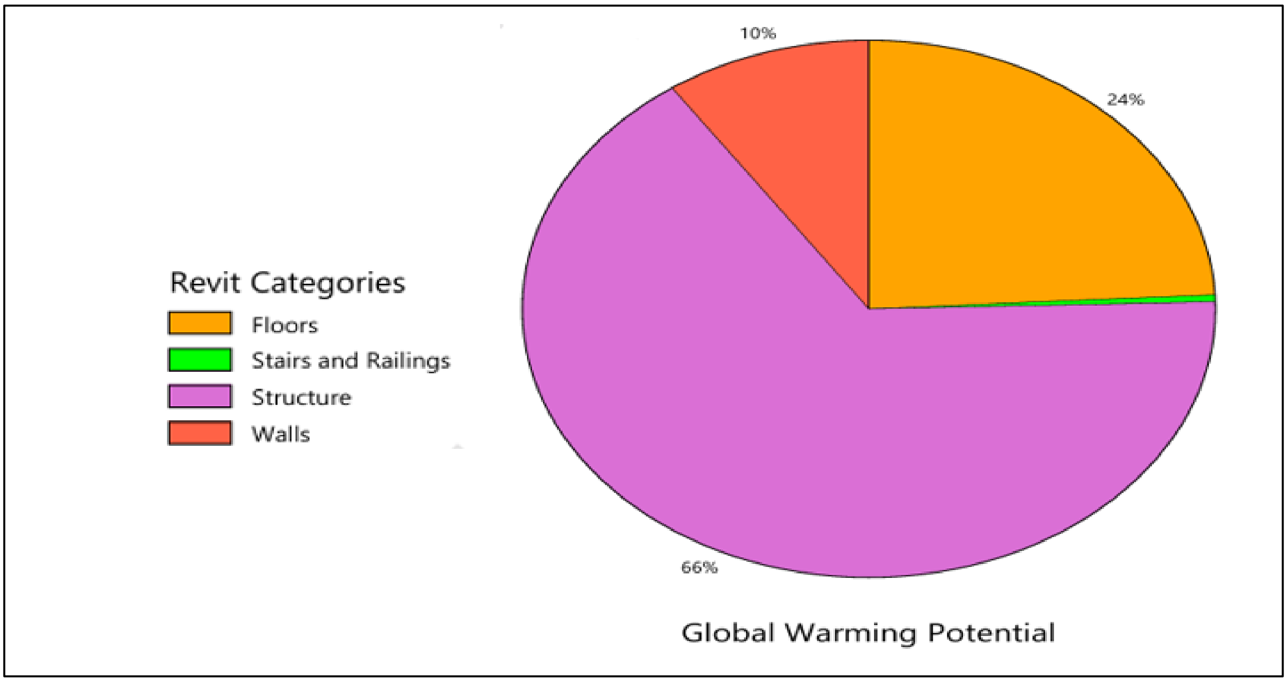

Fig 11 Elements' Total Global Warming Potential.

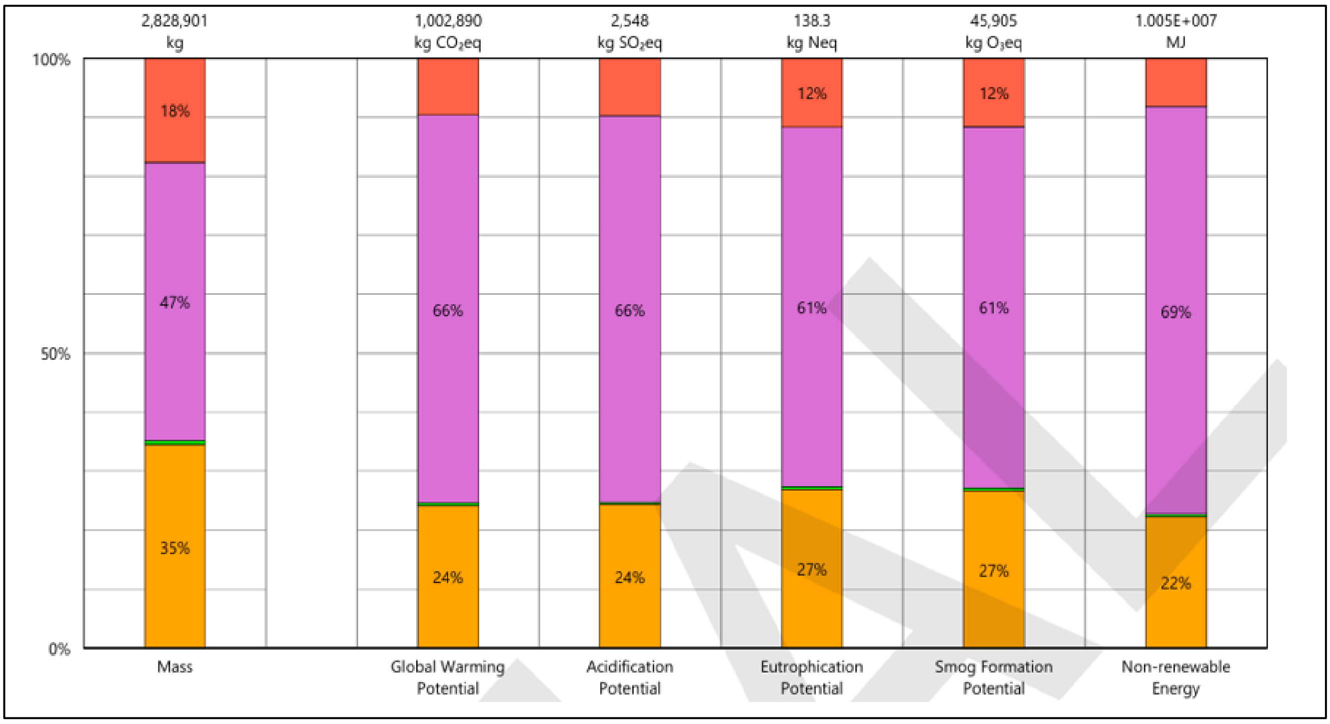

Fig 12 Element Detailed Global Warming Potential.

The structural parts make up a significant portion of the environmental impact. They account for approximately 66% of the total global warming effect, and are responsible for over 60% of acidification, more than 60% of eutrophication, and a significant share of smog formation. Their share in the use of non-renewable energy, at 69%, also highlights the energy-intensive structural materials, such as concrete and steel.

The second most influential category is floors, which contain 35 percent of the total mass and 24-27 percent of the most of the environmental measures. Walls comprise a relatively lower proportion of the environmental burden, although they contribute to it by about 10^12 per cent across all indicators, due to their 18 per cent share of the mass. Stairs and railings have a small environmental impact compared to them. The already mentioned pie chart of Global Warming Potential also highlights the prevalence of the structural system that contributed to two-thirds of the overall emissions. All these outcomes support the need to focus on structural systems and floors when it comes to the optimisation of materials and carbon reduction strategies in sustainable building design.

➢ *Operational vs. Embodied Impacts*

The environmental impact of a building is typically measured by two categories: operational impacts, which result from energy use throughout the building's life cycle, and embodied impacts, which stem from the production, transportation, and construction processes of the materials. For the Kuwait Villa, the Life Cycle Assessment (LCA) provides a striking disparity between these two categories.

- *Operational Impacts*

Operational energy, attributed to Stage B6, contributes the most to Global Warming Potential (GWP) and Primary Energy Demand (PED). Indeed, the villa consumes 107,209,876 MJ of energy and emits 6,980,810 kg CO_2eq over its 60-year life cycle. These figures represent 87.4% of the total GWP and 91.1% of the total PED, as shown in Table 3. These figures are equivalent to the calculated electricity energy consumption of 216.22 kWh/m²/year and the calculated heating energy consumption of 108.11 kWh/m²/year for use over a gross floor area of 555 m².

Such a trend is typical for buildings in warm climates, where the loads on cooling prevail over energy consumption. Current research bears witness to this trend: [32] found that energy consumption during operation in residential buildings in Saudi Arabia can contribute over 85% of life cycle emissions, especially if powered by fossil fuel-based grids. Operational energy in hot climates is higher than embodied emissions [33]

- *Embodied Impacts*

The impacts at stages A1–A5, C2–C4, and D are much smaller in scale, yet they remain meaningful. The Product stage (A1–A3) alone provides 684,205 kg CO_2eq and 7,484,372 MJ, representing 8.6% of GWP and 6.4% of PED. These are mostly due to structural concrete and steel reinforcement applications, which are high in embodied carbon. The Tally report indicates the following materials as the most critical, with concrete contributing over 558,000 kg CO_2eq and steel contributing over 444,000 kg CO_2eq.

Although less than 2% of GWP is associated with transportation (A4), construction (A5), and end-of-life (C2–C4) stages, these stages are not insignificant. Moreover, Module D realises partial compensation through recycling and energy recovery, reducing the net load by 202,875 kg CO_2eq and 1.77 million MJ.

Table 3 Operational vs. Embodied Impacts

Category	GWP (kg CO_2eq)	PED (MJ)	GWP (%)	PED (%)
Operational (B6)	6,980,810	107,209,876	87.4	91.1
Embodied (A1–A5, C2–C4, D)	1,007,363	10,415,144	12.6	8.9
Total	7,988,173	117,625,020	100	100

- *Implications for Design*

The strong dominance of operational effects means that energy efficiency should be the opening movement in warm climate building design. Embodied effects should not be neglected, though, especially at initial design stages where material choices are made. The following measures can be applied to reduce embodied emissions considerably:

- Using low-carbon concrete (such as geopolymer or high fly ash content)
- Specifying recycled steel
- Material selection with third-party certified Environmental Product Declarations (EPDs)
- Designing for disassembly and reuse.

Besides, passive cooling strategies, high-performance envelopes, and renewable energy systems can minimise operational impacts. The combination of passive design and solar PV can decrease operational GWP by as much as 40%, thereby increasing resilience and sustainability [34].

➢ *Scenario Comparison*

To contrast the potential minimisation of environmental effects in residential buildings, a comparative scenario assessment was conducted between the current villa layout and a recommended alternative low-carbon layout. This approach is commonly employed in Life Cycle Assessment (LCA) analysis to evaluate the effectiveness of design interventions [35].

✓ *30% Reduction in the Use of Concrete:*

This assumption reflects an achievable structural optimisation on the material level, for instance, thinning of the slab, voided slabs, or substitution of part of the concrete with alternative materials with lower impacts, like AAC.

✓ *50% Renewables Integration:*

This refers to the installation of solar photovoltaic (PV) systems on rooftops or other renewable energy sources to supply half of the building's operational energy needs. Operational energy-related greenhouse gas emissions and energy use are therefore doubled by 0.5, assuming that renewable energy resources contain zero carbon.

- *Environmental Impact Comparison*

The table below summarises the Global Warming Potential (GWP) and Primary Energy Demand (PED) for both the current and alternative design scenarios.

Table 4 Compression Between the Current and Alternative Design

Scenario	Concrete GWP (kg CO_2eq)	Operational GWP (kg CO_2eq)	Total GWP (kg CO_2eq)	Concrete PED (MJ)	Operational PED (MJ)	Total PED (MJ)
Current Design	1,002,889.74	6,199,308.49	7,202,198.23	10,347,743.54	93,601,638.00	103,949,381.54
AlternativeDesign	702,022.82	3,099,654.25	3,801,677.06	7,243,420.48	46,800,819.00	54,044,239.48

Alternative design results in a 47.2% reduction in overall GWP and a 48% reduction in overall PED from the current design. These reductions are mostly as a result of the significant reduction in operational energy emissions that characterise the life cycle impact in hot climates like Kuwait.

This scenario breakdown is presented to highlight the immense environmental benefits of implementing material efficiency and renewable energy. A reduction in concrete consumption means a reduction in both embodied carbon and production energy. In the meantime, installing solar PV or any other renewables directly displaces fossil-fuel electricity, which is the number one GWP determinant in operations [36].

- *Sensitivity and Uncertainty Considerations*

Being conditioned and influenced by a chain of assumptions and input variables, LCA results are somehow uncertain. This study has chosen, among others, some key parameters such as materials, energy consumption rates, and lifespan assumptions on the basis of standard values or modelled estimates. However, even if Tally brings a rich database and integration with BIM platforms, results concerning environmental impacts still get altered with changes in these inputs.

For instance, operational energy demand was modelled, assuming it consumed 216.22 kWh/m² of electricity and 108.11 kWh/m² of heating energy annually. These values represent a typical residential building in Kuwait, but may vary significantly depending on occupant behaviour, HVAC system efficiency, and future climate conditions. The ±10% variation in operational energy could translate to a shift of over 500,000 kg CO_2eq in total GWP, underlining the importance of correctly modelling energy.

ISSN No: 2456-2165 https://doi.org/10.38124/ijisrt/25jul181

Similarly, embodied impacts show sensitivity to the selection and sourcing of materials. Using U.S.-based life cycle inventory (LCI) data in Tally may not precisely capture the environmental portfolios of materials produced in the Gulf. Transport distances, production energy mixes, and recycling rates are highly variable and affect the precision of embodied carbon calculations.

- *To Address Such Uncertainties, the Following Studies must Incorporate:*

✓ Scenario-based modelling (such as best case, worst case)
✓ Monte Carlo simulations for probabilistic analysis
✓ Geo-specific LCI data to maximise regional relevance

Recognition and quantification of uncertainty are essential for making sound, well-founded design decisions and enhancing the credibility of LCA results in practice and policy.

V. CONCLUSION

In this study, the importance of Life Cycle Assessment (LCA) was highlighted when assessing the environmental performance of residential buildings in Kuwait. By using Autodesk Revit in conjunction with the Tally plugin, the researchers were able to present an exhaustive account of the environmental impacts exhibited at every stage of a building's life, from material extraction to disposal at the end of its life. It was found that the greatest phase of environmental degradation is the operation, which accounts for more than 87% of the total Global Warming Potential (GWP), particularly in relation to energy consumption for cooling.

The study also highlights the significant environmental pressure imposed by the materials of construction, with concrete and steel being the primary offenders. These materials earn their infamy due to their high embodied carbon and energy demands, thus calling for an alternative set of greener options. In addition, the study examined the scenario of reducing concrete usage by 30% and integrating 50% renewable energy, resulting in an almost 50% reduction in GWP and PED. This gives an insight into the use of design interventions for reducing environmental impacts.

The paper emphasises that green construction, particularly through Life Cycle Assessment (LCA), offers a practical approach to minimising the environmental impact of the construction industry in hot climates such as Kuwait. Incorporating energy-efficient systems, sustainable materials, and renewable energy sources can significantly enhance the longevity and environmental sustainability of residential developments. The results provide a valuable foundation for guiding future policymaking and architectural planning in the direction of environmental sustainability.

Based on the findings, there is a recommendation that the engineers and architects prioritise energy efficiency at the design stage, especially in hot climate zones like Kuwait. Passive design principles such as improved insulation, shading, and ventilation must be combined with high-efficiency HVAC systems. The deployment of renewable energy technologies, such as rooftop solar panels, has the potential to reduce operational emissions and fossil fuel consumption significantly. Moreover, environmental performance data should inform material selection, favouring low-carbon products with Environmental Product Declarations (EPDs). Reducing the use of concrete and steel through structural optimisation and the integration of recycled or alternative materials will help diminish environmental burdens.

In theory, future research must explore how Life Cycle Assessment (LCA) methodologies can be mainstreamed in early design for different building types and climates. Models need to be developed to combine dynamic energy simulation, local climate information, and occupant behaviour for improving the predictive capacity. Scientific investigation into the long-term performance of low-carbon materials and renewable systems in arid conditions will further enhance the theoretical foundations of sustainable design. Additionally, the optimisation of BIM-connected tools, such as Tally, and the development of regional LCA databases will facilitate more context-specific and evidence-based decision-making in sustainable architecture.

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