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Retrofit of Building Façade Using Precast Sandwich Panel: An Integrated Thermal and Environmental Assessment on BIM-Based LCA

Quddus Tushar, Guomin Zhang *, Muhammed A. Bhuiyan, Satheeskumar Navaratnam, Filippo Giustozzi and Lei Hou

School of Engineering, RMIT University, Melbourne, VIC 3001, Australia
* Correspondence: kevin.zhang@rmit.edu.au

Abstract: The study conducts a comprehensive life cycle assessment (LCA) of precast sandwich panels by integrating operational and embodied phases detailing thermal efficiency and environmental impacts. The analytical regression model is developed for climatic diversity and design variables using the energy rating tool *FirstRate5* to compare with a conventional brick veneer construction. LCA is performed on the building information modeling (BIM) platform to connect operational energy and express the relative embodied impacts of insulation constituents, compressive strength, reinforcement, and mix design. Monte Carlo simulation shows significant advantages of concrete sandwich panels in reducing operational H/C loads over building service life. LCA reveals a 100 mm thick external precast concrete wall with 50% fly ash reduces CO_2 emission and energy demand by 54.7% and 75.9% consecutively against the benchmark. Moreover, it comprises 84.31% of the total building mass, accountable for only 53.27% of total CO_2 emission and 27.25% of energy demand, which is comparatively lower than other materials. In the case of selecting lining insulation, a broader benefit is identified for extruded polystyrene (XPS) and expanded polystyrene (EPS) boards due to their relative weight, thickness, and environmental impacts. Representative equations of energy efficiency and impact assessment will assist in adopting sandwich panels for new construction and refurbishment with relative dimensions.

Keywords: precast sandwich panel; life cycle assessment (LCA); thermal simulation; multiple linear regression analysis (MLRA); sensitivity analysis; optimization

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1. Introduction

The growing demand for housing and the projected population growth contribute to more energy consumption in the construction sector. The direct or indirect energy calculation of manufacturing products and services in the construction supply chain has become an emergent research theme [1,2]. Life Cycle Assessment (LCA) is a crucial component in identifying the embodied energy of building materials through resource consumption, potential emissions, and waste generation [3,4]. Generally, building materials with a high thermal mass, such as concrete, contain a higher embodied energy. Thermal mass is the ability of materials to absorb and release their total storage heat in one day [5]. Dense materials such as bricks, concrete, soil, and rocks require a lot of heat energy to change their temperature. Therefore, it is recognized that these high-density materials have a high thermal mass. In comparison, lightweight materials, such as wood, are known as low thermal mass materials [6]. The thermal mass acts as a rechargeable thermal battery. In summer, it absorbs solar heat during the day and releases heat in a cool breeze on a clear night, keeping the home comfortable. In winter, the thermal mass is a heat storage source of solar radiation and emits this radiation on cold nights to keep the house warm. A material with a high thermal mass is generally not a better thermal insulator, such as rammed earth [7]. Thermal mass cannot be considered a substitute for insulation [8] because it absorbs and releases heat, while insulation is a barrier to heat flow from outside to inside. Therefore, thermal mass benefits can be achieved when there is a significant difference between the outdoor temperature during the day and night [9,10]. Thus, selecting a suitable thermal mass with an adequate level of insulation can guarantee year-round thermal comfort for the occupants and a significant difference in energy costs for heating and cooling (H/C).

The precast concrete structure has a greater volumetric heat capacity (2060 $KJ/m^2{\cdot}K$) compared to other commonly used building materials such as brick (1360 $KJ/m^2{\cdot}K$) [5]. The precast concrete structure is expected to offset the initial material's embodied energy by reducing the mechanical heating and cooling system over the building service life. In addition, the structural panel provides a high-quality interior finish and a smooth shape to improve the thermal bridge of the insulation without interruption, assuring the thermal comfort of the residents [11]. Since a concrete structure can withstand a hundred (100) years [12], using such facilities can lead to conserving resources and reducing waste. Disassembled precast panels facilitate environmental and economic savings by using them after the end of their useful life as crushed aggregate for concrete mix, road pavement, or backfill [13]. A detailed life cycle assessment (LCA) analysis is required for the precast concrete panel to estimate operational benefits by integrating an environmental impact assessment of embodied phase. In addition, an innovative approach to incorporating waste such as slag and fly ash into the precast concrete is to be justified from energy and emission perspectives.

A well-designed insulated building provides year-round comfort, halves heating and cooling energy bills, and significantly reduces greenhouse gas emissions [14]. The effectiveness of insulation depends on several interacting factors, such as thermal bridges, ventilation, vapor barrier, air gaps, and physical treatment of the insulation [8]. Therefore, the recommended *R*-value of the building façade according to the insulation code (ICANZ) is challenging to achieve in a traditional building system [15]. The Sandwich panel consists of three layers, two panels of concrete, each with a layer of mesh, and an insulation layer between two panels of concrete. These sandwich panels are commonly used to erect walls where construction uses ordinary reinforced concrete or cold-formed steel frame per the design requirements [16,17]. Dowels bars connect these panels, and mortar is sprayed with temporary support to cast these panels in building fabrication. Manufactured sandwich panels are 1.2 m (4 ft) in length and 2.4 m (8 ft) in height, available in various thicknesses from 50 mm to 150 mm (2″–6″). The load-bearing capacity of precast concrete sandwich walls varies between 40,000–120,000 lbs per linear foot. It also withstands hurricane winds of 200 miles per hour (mph) and earthquakes of 7.5 rector scales. Erection of sandwich panels building requires less time than brick or wooden framed structures. Usually, a month is spent erecting a building much lower than concrete blocks. Conjugate application of insulation and concrete enhances the opportunity of performing better due to line sealing and thermal mass.

Considering the sandwich panel's innovative and state-of-the-art lining insulation, it is suitable for its structural compatibility, effective thermal comfortability, and shorter construction time compared to conventional brick or reinforced cement concrete (RCC) construction. However, the linkage between the manufacturing and service phases has been overlooked in these studies for sustainable decision-making. Therefore, the study develops the BIM model to compare and assess the embodied impacts of the manufacturing stage and the operational efficiency of sandwich panels over conventional construction.

The prefabricated sandwich panel avoids the thermal bridge by continuing the core insulation between the outer and inner layers of the outer wall [18,19]. The precast sandwich panel consists of an outer layer of 50 mm concrete, 70 mm core insulation, and an inner layer of 75 mm concrete [20]. The arrangement can achieve a recommended *R*-value of just 2.95. Different types of thermal insulations are used as core materials in composite sandwich panels and building fabrics, such as cellulose fiber, glass fiber, polyurethane foam, expanded polystyrene (EPS), and extruded polystyrene (XPS) [21]. Cellulose fibre insulation is created by recycling paper into fibers. Glass (silicate) is molten to develop glass fibre, which is the most commonly used insulation nowadays. Polyurethane foam is produced from raw materials such as Polyethylene terephthalate (PET), tackifier, and talcum powder. Recycling disposable PET bottles are feasible to process into high-quality polyurethane foam, reducing the requirements of virgin materials and production costs. These foams are used in composite sandwich panels, building insulation, turbine blades, surfboards, and high-speed train structures. However, the density of PET foam is relatively higher than XPS or EPS foam; it is almost three times that of XPS. Even the water absorption of producing raw materials is comparatively high, and a dry fluidized bed is used to soak water below 50 ppm. Closed cell spray applied polyurethane foam is produced as insulation through this process, which causes comparatively higher emissions than others. EPS and XPS are closed-cell structures with better compressive strength. EPS is more permeable to moisture and air, whereas XPS is resistant to vapor. However, relative uncertainties of emissions and energy to achieve a recommended R-value of insulation application are required to be justified from the sustainability perspective. Therefore, the study performs a sensitivity analysis to assess the variations in environmental impacts on insulations applications.

Fly ash acts as a supplementary cementitious material in concrete. Structural concrete gains significant strength due to the pozzolanic reaction of fly ash with cement. Amorphous-alumino-silicate reacts with calcium hydroxide released by cement hydration, and it produces two binding components, calcium-silicate-hydrate (C-S-H) and calcium-aluminum-hydrate (C-A-H) [22]. An experimental study shows that increasing the ratio of fly ash (50%) as a substitute for cement can be used without compromising the mechanical properties of concrete. Increased proportions of fly ash (25%, 30%, and 50%) in concrete result in lower environmental impacts [23]. It is due to the savings from coal extraction, manufacturing, and combustion processes. Therefore, the study aims to identify the variations in the environmental impacts of adopting proportions of fly ash in concrete structures from a sustainability view. Moreover, multivariate regression analysis has been performed on energy simulation data to determine the insulation level (R-value) association with sandwich panels. The findings of this study are expected to set up the benchmark for manufacturing sandwich panel in terms of thermal efficiency, environmental benefits, and selecting lining insulation.

2. Precast Concrete Panel—A Critical Review

Precast concrete wall, floor, and ceiling panels provide a durable and long-lasting solution for all typical residential construction, from single-family homes to multi-story apartments [24,25]. The high initial embodied energy of concrete can be offset by extending the life of the building to 100 years and has great potential for reuse and renovation [26]. The innovative design approach of the precast elements in the initial development phase is crucial to ensure meeting standards, extend the life of the building without renovation, and reuse components in the demolition phase. This study aims to quantify the potential benefits of prefabricated components over conventional components through a comprehensive life cycle assessment (LCA). Additionally, it determines whether this prefabricated insulation panel or sandwich panel offers better operational efficiency and environmental performance than traditional building practices. In addition, it suggests the improvement of the prefabricated structural panel by including fly ash and insulation materials.

2.1. Energy Rating Tool

Early evaluation of thermal simulation provides valuable information for the decision-making in the design phase; otherwise, it can significantly impact energy consumption and costs later in the operational phase [27,28]. A dynamic simulation engine's simplified graphical user interface can efficiently estimate consumption by reducing the required input variables. It makes the process more intuitive for assessors or designers, narrowing the linking gap and enabling faster simulation output [29,30]. Challenges identified for this type of simulation include (1) clients being reluctant to pay for energy simulation and

(2) bridging the gap between design and energy simulation to generate a working energy model throughout the process quickly [31].

Nationally recognized rating tool *FirstRate5* is a user-friendly interactive tool that integrates CSIRO's Chenath AccuRate simulation engine to calculate the annual heating and cooling energy load to evaluate an existing design or optimize beyond compliance [32,33]. The study applies the *FirstRate5* energy rating tool to facilitate the broader appearance of precast concrete panels by enabling parametric analysis of entire building components, ceiling, walls, and floor. However, the specific estimate of thermal load at the conceptual stage of the design is not an adequate indicator to make meaningful suggestion for future decision-making. The analytical approach and the energy consumption model have been developed in this study to be relevant for a design decision to justify the energy simulation as a practical design tool.

2.2. Regression Analysis in Energy Optimization

Several studies have performed multiple linear regression analyses (MLRA) to identify design parameters influencing building energy consumption. The dynamic model data's accuracy is used to predict H/C load based on best-fit regression equations. Regression analysis aims to present a function that establishes a relationship between the dependent and independent variables [34,35]. An extensive study in France developed a regression model for residential buildings to predict the monthly energy consumption for heating, taking into account the *U*-value of the building envelope, the window-to-wall ratio (*WWR*), and the building shapes [36]. Another study used *EnergyPlus* simulation software to develop linear and nonlinear regression models to estimate the energy load of a typical office building by controlling daylight [37]. A government-supported study in Brazil established regression equations to identify factors influencing the energy consumption of the building envelope, such as size, building design, solar heat gain coefficient, and roof heat transfer coefficient [38]. A study used detailed simulations to form regression equations to predict the annual energy consumption of a building under certain climatic conditions in central India [39]. The regression equations developed in the study seemed perfect, with a coefficient of determination greater than 0.9. Lam used the *DOE-2* Energy Simulation Tool for the Variation of five Climate Zones in China to study the impact of design variables on the energy efficiency of buildings and identified the Shading Coefficient (SC), and windows-to-wall ratio (WWR) were the most influential factors on a building's energy consumption [40,41].

However, most previous studies rarely focused on the correlation between energy consumption and façade components variations for climate diversity. The present study performed multiple linear regression analysis (MLRA) to develop equations to overcome these obstacles and predicts energy consumption for three typical Australian climate zones such as hot, warm, and cold temperate. Ongoing research considers insulation level (*R*), *WWR* variation, temperature, facade materials such as brick veneer, precast structural panels, and other dynamic properties. In particular, parametric regression analysis uses simulated energy data from *FirstRate5* to determine the association of pre-designed and conventional building facades with influential design parameters (*R*, *WWR*) influencing the total energy load of a building.

2.3. Monte Carlo Simulation

Monte Carlo simulation is a sample-based method of running the model multiple times with a random selection of input variables [42,43]. The simulations provided probable explanations for various mathematical solutions through statistical data sampling on the computer [44,45]. Sensitivity indices validate uncertainties in energy models in rational decision-making, provide design details for individual buildings [46], provide design details for individual buildings [47], and have uncertain effects on the physical properties of building materials after construction [48]. The sensitivity analysis results cannot be used as a general tool readily applicable to the newly designed building [49]. However, the subsequent outcomes of uncertainty analysis yield some in-depth insights into the posterior impacts of building energy performance. In this study, Monte Carlo simulation has been performed to obtain the confidence interval and sensitivity indices of the developed models.

2.4. Life Cycle Assessment (LCA)

Life cycle assessment (LCA) is a systematic approach to assess the environmental impact of a product throughout its life cycle, from the extraction and processing of raw materials (cradle) through production, transportation, construction, and operation to recycling or disposal of materials (grave) at lifespan end [50,51]. However, conducting LCA is time-consuming and labour-intensive when applied to complex systems, such as the entire life cycle of a building. Additionally, selecting suitable emission factor standards for construction related work is often complicated, due to the lack of emission inventory data in many countries and regions [52]. Comprehensive LCA is relevant for variation in system boundaries, data collection diversity, and data mapping from one life cycle stage to another, region to region, or environmental factor to another [53]. The end-of-life phase of LCA includes collecting, processing recycled materials, incineration, and disposal of waste in landfills. The impact of disposal is calculated based on the average properties of inert and biodegradable plastic waste. Therefore, LCA is considered an idealistic method to assess the holistic potential of offsite prefabrication processes to reduce waste generation.

Building Information Modelling (BIM) provides a platform to develop the LCA process of buildings in a simplified manner [54,55]. Better interoperability between BIM-compliant LCA and energy simulation tools can accelerate the calculation of total life cycle energy demand for various architectural BIM model products, reducing user-specified energy simulation input requirements [56]. The use of BIM-enabled LCA significantly reduces effort and time for professionals when performing LCA for the entire building. Conventional LCA workflows, such as inventory analysis, are complicated and can only be specified after construction [57,58]. The BuildingSmart Institute has developed an open data schema for LCA, known as Industry Foundation Classes (IFC), to create interoperability between BIM and energy analysis tools [59].

In compare to IFC, Green Building XML (gbXML) is another integrated BIM data source to process information only for energy evaluation [60]. However, the BIM software, *Tally*, provides an interactive, self-contained LCA process that leverages the resources used in the project phases and links the operation to the integrated phase through the energy simulation tool [61,62]. The innovative LCA *Tally* tool leverages BIM's ability to extract materials from the model and bridges the gap between the virtual model and reality [63].

The Life Cycle Inventory (LCI) data used to develop the LCA model for conventional and prefabricated sandwich panels is organized according to mappings from the GaBi 6 database and modeling principles [64]. The database is sourced from the manufacturing industry through interviews and meetings of experts involved in processing. The electricity consumption of equipment used in quarries and mixing plants are considered as fuel consumption for production per one cubic meter (m^3) sandwich panel unit. The average fuel consumption per hour of vehicles, machine efficiency, and working hours are the essential factors of LCI. The scope of this LCA approach is created in the Ecoinvent databases that deliver materials from cradle to gate. At the end of this life cycle, materials are disposed of in landfills. Reuse and recycling of these materials have not been considered in this study. The expected lifespan of the building service is taken as 60 years. However, the service life can be extended per the LCA practice. Eventually, at the end of a life cycle, prefabricated sandwich panels have advantages over other conventional construction for reuse and recycling. Metal accessories, hardware, casting, and sealants are out of the project scope.

The conceptual framework of this study proposes a specific methodology to assess significant impact categories, environmental benchmarks such as primary energy demand (PED), and global warming potential (GWP) for the variation of precast elements from conventional construction by performing an LCA on the BIM platform. The application of precast concrete panels is justified by comparing and verifying the properties and functions of different building materials.

3. Research Methodology

A methodological flowchart has been developed to present the steps and activities of this study, as shown in Figure 1. The study is structured as follows:

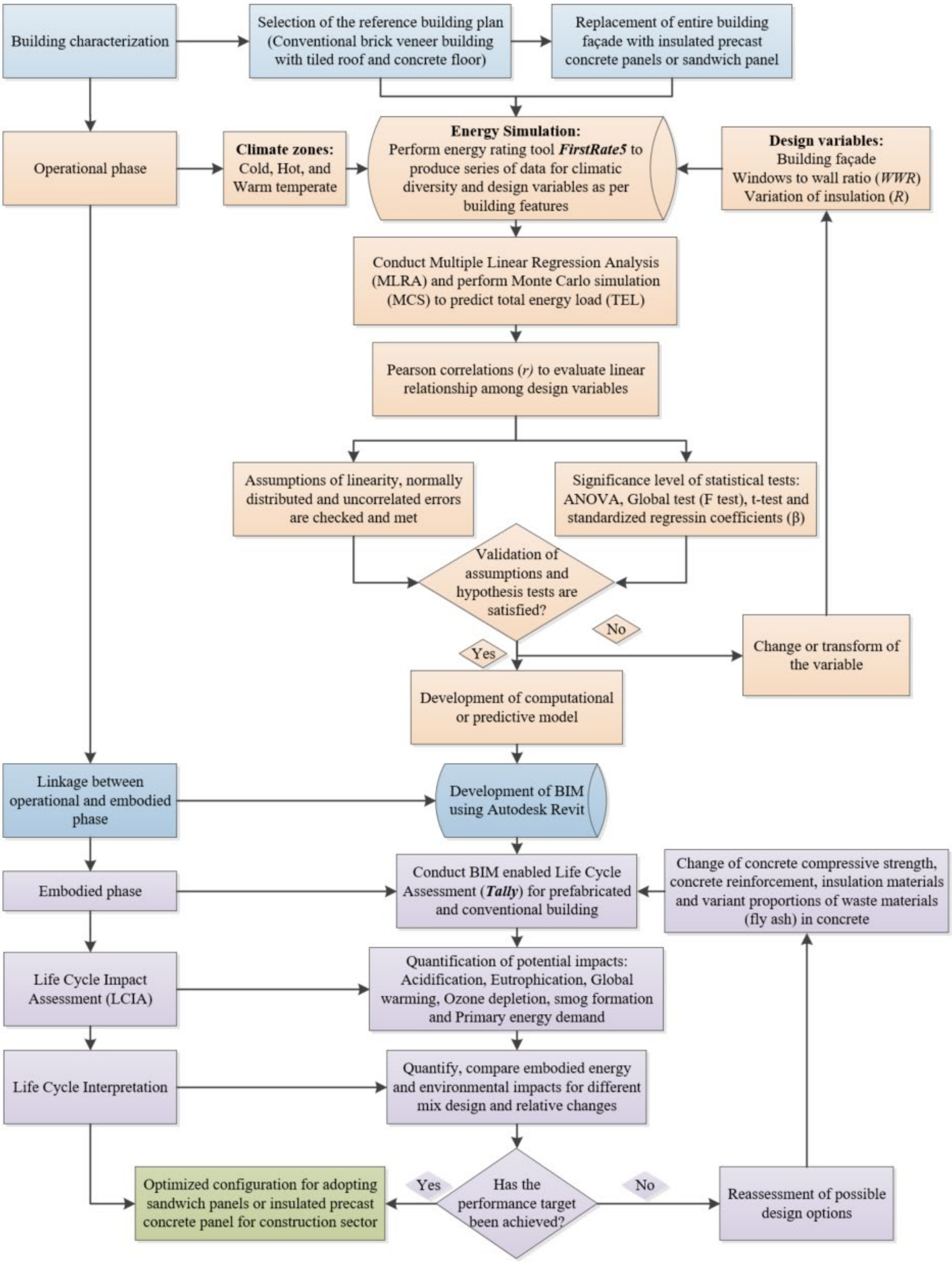

Figure 1. An analytical framework to determine the optimized configuration of precast concrete panels.

Firstly, the regression model development for the variation of design parameters such as windows to wall ratio (*WWR*) and level of insulation (*R*) for different components of the traditional and the precast buildings. The regression analysis has been performed within the simulated data of energy rating software *FirstRate5*. Performed regression analysis is a significant indicator of the design parameters' association with a building's energy consumption.

Secondly, a detailed Monte Carlo simulation has been performed *@RISK* palisade decision tool to obtain the sensitivity indices for selected design parameters and their corresponding ranges. The results of the Monte Carlo simulation provide an extensive set of data to validate the regression model through the confidence interval and correlation coefficients.

Thirdly, a baseline model is developed by *Autodesk Revit* (BIM) to identify the associated life cycle impacts for both conventional and prefabricated structures, applying additional plug-in *Tally*.

Finally, the study quantifies the reduction of embodied energy by incorporating recycled materials (fly ash) in precast concrete and cast-in concrete construction. It further clarifies the association of embodied energy with the variation of reinforcement, the compressive strength of concrete, and insulation materials as per design specification.

3.1. Estimation of Operational Energy

In this study, the base house is a single-story residential dwelling in the suburban terrain of Melbourne. The conventional house is erected with 110 mm brick veneer (BV) external walls, 100 mm thick concrete slab on the floor, concrete tiles on the roof, and single glazed Aluminium framed windows. The typical building consists of four bedrooms, two toilets, living, kitchen, dining, garage, and others with a total gross floor area of 228.1 m^2, as shown in Figure 2.

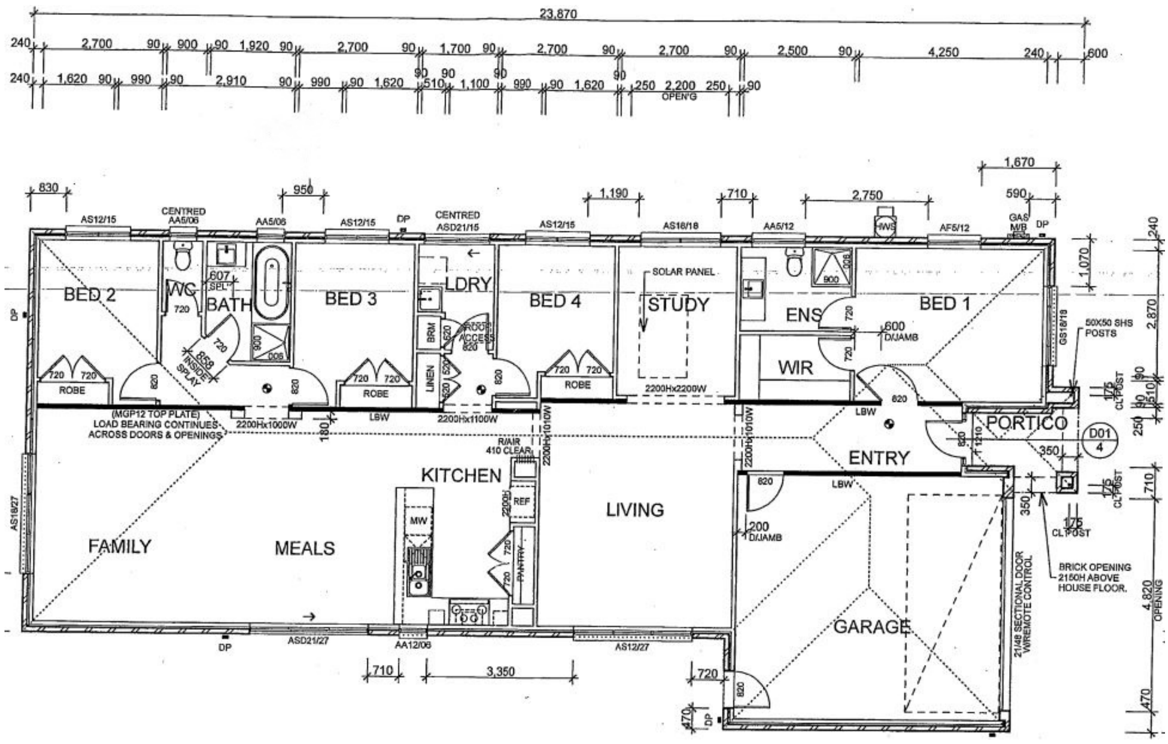

Figure 2. Floor Plan of the case study house.

FirstRate5 is selected for energy simulation due to its simple graphical user interface and database to develop energy rating equations with selected design parameters. The building plan has been imported to the drawing canvas of *FirstRate5* to estimate the energy consumption per the Nationwide House Energy Rating Scheme (NatHERS) standards. The energy consumption of a house depends upon the properties of the building façade due to the year-round heating-cooling requirements. The assigned building is alienated into conditioned and unconditioned zones as per the occupancy types, as shown in Table 1. The entire building façade is replaced with concrete panels to identify the potential thermal impacts of precast concrete panels over the conventional. Subsequently, the building is assessed to determine the variation of energy consumption for a different insulation (*R*) level and *WWR* of the building plan.

Table 1. Conditioned and unconditioned areas to estimate operational energy.

Type of Area	Area (m^2)
Net conditioned floor area (NCFA)	181.0
Unconditioned room area	7.7
Garage area	39.4
Total gross floor area	228.1
Building façade components	**Area (m^2)**
External Brick Veneer (BV) wall	161.0
Internal plasterboard stud wall	183.8
Concrete Slab on Ground (CSOG) floor	228.2
Windows (Aluminium Single Glaze Clear)	50.74

3.2. Multiple Linear Regression Analysis (MLRA)

In this study, energy consumption models have been developed by performing multivariate regression analysis in the IBM *SPSS* statistics tool for both the traditional BV and the precast concrete construction. The resultant energy prediction models are developed on a detailed simulation that considers the dynamic thermal interactions of design parameters (*R*, *WWR*) and different temperate zones within an accredited energy simulation software *FirstRate5*. The Pearson correlation coefficient (*r*) and the coefficient of multiple determination (R^2) show a reasonable fit for linear regression in predicting energy consumption as a function of design parameters. The general form of the linear regression Equation (1) is as follows:

$$Y = f(x) = b_0 + \sum_{n=1}^{j} (b_n x_j) = b_0 + b_1 x_1 + b_2 x_2 + \ldots + b_n x_n \quad (1)$$

where Y is the thermal energy load (*TEL*), or energy consumption, and b is the regression coefficient for the corresponding design variable (x). The regression coefficient is identified by using the least square method by minimizing the sum of squared residuals error.

The analysis relates the variations of predictors (*R*, *WWR*) to the thermal energy load (*TEL*) or consumption. The multiple linear regression analysis has been performed to achieve the best-fitted equation to explain the variation in energy consumption for design variables. However, once being developed, it can function independently for large to the small scale of any prefabricated or conventional model. The developed linear energy model can be applied as a supportive instrument of design tool that provides fast and energy-relevant assumptions at the early design stage.

3.3. Sensitivity Indices

Monte Carlo simulation has been performed in *@RISK* to obtain the sensitivity indices of the developed model. It iterates such models to create thousands of scenarios that might arise instead of a single "best outcome" scenario. After performing all the iterations, results have been presented numerically and graphically. It shows the variation of energy consumption from the smallest (5th percentile) to the highest (95th percentile) by a confidence interval, the mean, the standard deviation, coefficient variation, Pearson correlations for overall iterations. Besides these, the sensitivity analysis allows anyone to select the proper design variable to achieve the desired energy consumption.

3.4. Development of Building Model

Autodesk Revit (BIM) has been used to develop two basic models, both conventional and precast concrete, to quantify, compare, and improve the construction system. Insulated precast sandwich panels and single layer panels of 100–125 mm thick are commonly used around Australia for residential building construction, as shown in Figure 3. Two types of precast concrete panels have been used in this study to develop the Revit model. Sandwich wall panel consists of three layers, and it differs from a single layer precast panel by providing continuous insulation between inner and outer layers of precast concrete, as shown in Figure 4. In that case, the sandwich panel can achieve better thermal efficiency by avoiding thermal bridges through the conjugate erection of precast panels and insulation. Therefore, the study has considered thickness, weight, and impacts of different insulation materials to suit the sandwich panel for easier lifting.

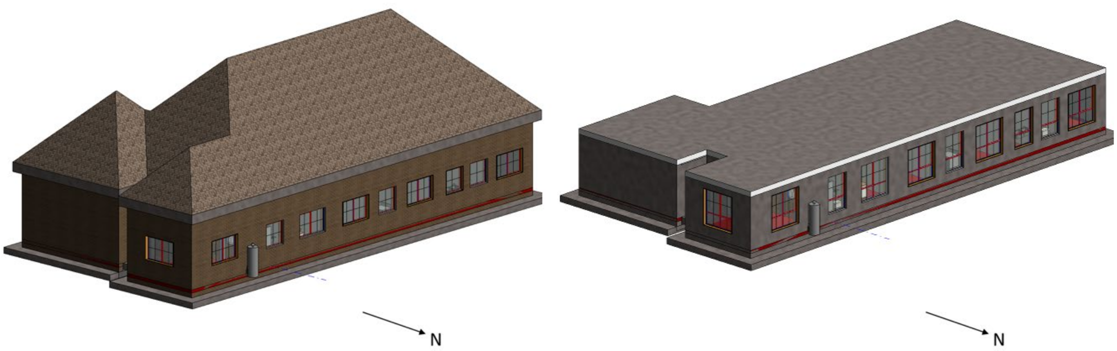

Figure 3. Development of building models (conventional and precast) in Autodesk Revit (BIM).

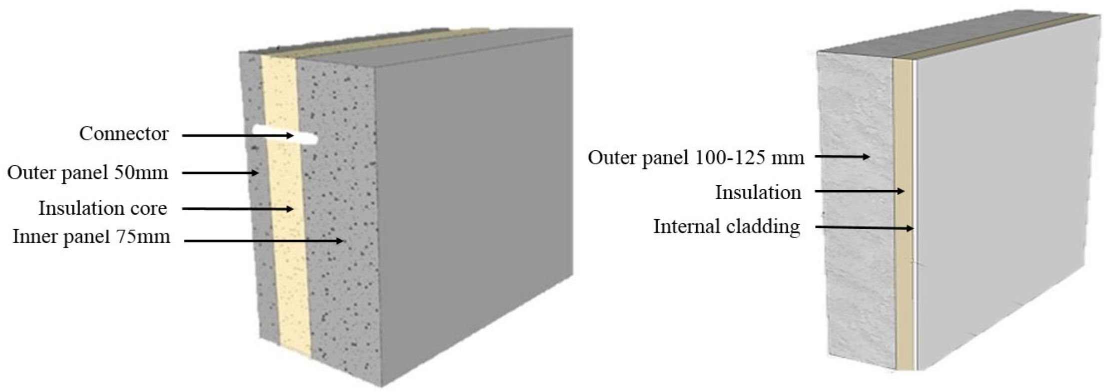

Figure 4. Insulated precast concrete panels (sandwich and single layer precast panel).

3.5. Estimation of Embodied Energy

The typical LCA process is a sequence of schematic design, design development, construction documents, and post-construction, which cannot be determined before construction [65]. The research connects BIM elements to Revit API programming (*Tally*) with a customized database of LCA. BIM-enabled *Tally* is consistent with LCA's ISO 14040-14044 standards [66]. According to ISO standards, LCA takes place in four different phases: (I) Goal and scope definition; (II) Inventory analysis; (III) Impact assessment; and (IV) Interpretation [67,68]. GaBi LCI databases have been used in the applied model widely used worldwide for industrial and scientific purposes and reviewed critically by published studies [69]. The Revit model estimates the environmental impacts of the prefabricated concrete panel with the variation of thickness, insulation, fly ash, and uncertainties of the model that have been reduced by applying technical, geographical factors of greenhouse gas account. Therefore, the research draws an in-depth analysis of LCA from the cradle to the grave of the off-site prefabricated structural concrete panel compared to a conventional system.

4. Results and Discussions

4.1. Regression Model

The regression analysis in this study aims to develop energy prediction models for conventional and prefabricated buildings. Besides these, regression models predict the fluctuation of energy demands with the individual building design parameters such as insulation (*R*) and windows to wall ratio (*WWR*), as shown in Table 2. Energy rating equations have been developed in the *IBM SPSS* statistics tool to predict the annual energy consumption of the building for the variation of climatic zone such as cold (Melbourne), hot (Darwin), and warm (Perth) temperate. The corresponding regression coefficient of the design variable shows the difference in thermal energy load (TEL) with each unit change of the design variable, while others remain constant. Linear combinations of design variables (*R, WWR*) have been justified by analysing variance (ANOVA) for the overall significance of the models. The two-tailed "t distribution test" shows that both design variables significantly contribute to energy prediction. Conventionally, the design variables with a *p*-value higher than 0.05 are statistically nonsignificant and dropped down from analysis. All the relevant assumptions of multiple linear regression analyses have been met and checked, including normality, linearity, independence, and uncorrelated errors. The adjusted *R*-square value of the model is 0.980, indicating that the model can explain 98% energy consumption variation. It is a substantial effect of design variables. The standardized β coefficient presented in the table recommends that *WWR* contributes more than the insulation (*R*) level to predict energy consumption.

Table 2. Energy consumption model in Melbourne from the effect of insulation (*R*) and windows to wall ratio (*WWR*) in percentage (%) as independent variables.

Model Summary						
Model	R	R Square	Adjusted R square	Standard Error of the Estimate	R Square Change	F change
Melbourne_BV	0.991	0.981	0.980	7.7285	0.981	660.566
ANOVA						
Model	Indicators	Sum of Squares	df	Mean Square	F	Sig.
Melbourne_BV	Regression	78,911.513	2	39,455.75	660.566	0.000
	Residual	1493.255	25	59.73		
	Total	80,404.767	27			
Coefficients						
Model	Indicators	Unstandardized Coefficients		Standardized Coefficients	t	Sig. *p*-value
		B	Standard Error	Beta		
Melbourne_BV	Constant	105.239	5.154		20.420	0.000
	WWR	2.653	0.078	0.932	34.193	0.000
	R	(−)18.005	1.461	0.336	(−)12.328	0.000

In this study, regression Equations (2)–(10) have been formed to measure the quantitative variation of energy consumption with the change of design variables such as level of insulation (*R*) and windows to wall ratio (*WWR*) for climatic diversities. Developed equations show that precast concrete building has a relatively higher association between energy reduction and insulation than traditional one. For example, for each additional insulation value, energy consumption decreases by 18.005 MJ/m^2 (Equation (2)) in the brick veneer construction of Melbourne. In the case of precast and prefabricated sandwiches, they are 21.462 and 20.598 MJ/m^2, respectively (Equations (3) and (4)). Darwin also performs a similar association in energy reduction with insulation in the hot temperate zone. However, the percentage of windows to wall ratio (*WWR*) is an intensified factor for energy consumption in Darwin than in other zones (Equations (5)–(7)). For example, each additional value of *WWR* in Darwin contributes to increased energy consumption by over 7 MJ/m^2, which is relatively higher than in Melbourne and Perth. In a warm temperate zone like Perth, the effect of insulation is not as influential as Melbourne and Darwin. For the prefabricated sandwich panel, every additional insulation unit decreases 7.377 MJ/m^2 (Equation (10)). On the contrary, the increase in the percentage of *WWR* causes additional energy consumption of 3.001 MJ/m^2.

Heating dominated (Cold temperate zone Melbourne):

$$TEL(Melb\_BV) = 105.239 + 2.653 \times WWR - 18.005 \times R \tag{2}$$

$$TEL(Melb\_Precast) = 126.020 + 2.577 \times WWR - 21.462 \times R \tag{3}$$

$$TEL\ (Melb\_Sandwich\_R\ ) = 121.831 + 2.508 \times WWR - 20.598 \times R \tag{4}$$

Cooling dominated (Hot temperate zone Darwin):

$$TEL(Dar\_BV) = 338.140 + 7.458 \times WWR - 14.486 \times R \tag{5}$$

$$TEL(Dar\_Precast) = 389.746 + 7.359 \times WWR - 22.621 \times R \tag{6}$$

$$TEL\ (Dar\_Sandwich\_R\ ) = 384.044 + 7.425 \times WWR - 21.023 \times R \tag{7}$$

Both heating-cooling dominated (Warm temperate zone Perth):

$$TEL(Per\_BV) = 32.823 + 3.326 \times WWR - 6.614 \times R \tag{8}$$

$$TEL(Per\_Precast) = 57.963 + 3.104 \times WWR - 9.202 \times R \tag{9}$$

$$TEL\ (Per\_Sandwich\_R\ ) = 50.387 + 3.001 \times WWR - 7.377 \times R \tag{10}$$

4.2. Validation of Regression Model

In the succession of model development, validation is conceivably the most crucial step towards a justification for practical applicability. The model validation process includes the fitness of the regression by verifying random regression residuals and justifying predicted values of the model, which have not been applied in the model for estimation. In this study, the model has been validated by the predicted data against the simulated values. Moreover, the coefficient of multiple determination (R^2-values) over 0.95 illustrates that the independent variables can thoroughly explain the energy consumption variation. The relative R^2-values for different construction methods have been presented in Table 3.

Table 3. Coefficient of Multiple Determination (R^2).

	Traditional Brick Veneer (BV) Construction	Precast Construction	Prefabricated Sandwich Panel Construction
Melbourne (cold temperate)	98.0%	97.2%	97.4%
Darwin (hot temperate)	99.7%	99.5%	99.6%
Perth (warm temperate)	99.5%	99.2%	99.4%

4.3. Sensitivity Analysis

Exhaustive sensitivity analysis has been performed in the *@RISK* palisade decision tool to compare the thermal efficiency from two different perspectives, as shown in Table 4. The result shows the energy consumption association between varying insulation levels in traditional and prefabricated panel construction. Standardized beta coefficients have been considered to compare the individual impacts of each independent variable (*WWR*, *R*) to thermal energy load (*TEL*). The higher value of the beta coefficient (β) over 0.9 expresses the increased rate of *WWR* has a substantial effect on consuming energy more than other design variables. Besides these, the increased level of insulation has a negative relationship with energy consumption. Such as, a beta of (−) 0.39 for prefabricated panels has a relatively higher impact on reducing energy consumption than a beta of (−) 0.33 for brick veneer construction in Melbourne. The model's beta defines an increased standard deviation of *R*-value; energy consumption decreases by 0.39 standard deviation. The assumption is made by considering other variables held constant. A comparative coefficient variation (CV) result indicates that the traditional structure always has a higher CV than the precast concrete structure, irrespective of climatic zones. The sandwich and precast concrete panels have less deviation relative to their mass and are more acceptable than the brick veneer.

Table 4. Correlation coefficients of sensitivity analysis.

Feature Climatic Zones	**Cold Temperate Melbourne**			**Hot Temperate Darwin**			**Warm Temperate Perth**		
Building components	Brick veneer	Sandwich panel	Precast panel	Brick veneer	Sandwich panel	Precast panel	Brick veneer	Sandwich panel	Precast panel
	Standardized Coefficients Beta								
WWR	0.932	0.905	0.902	0.993	0.986	0.985	0.992	0.989	0.984
R	−0.336	−0.395	−0.399	−0.103	−0.152	−0.161	−0.105	−0.129	−0.155
	Sensitivity indices for heating-cooling load								
Mean (μ)	174.11	177.99	182.98	622.06	642.47	649.08	159.06	160.80	168.20
Std (σ)	54.01	52.50	53.97	143.64	140.69	142.96	64.07	58.03	60.22
Coeff. of Var (CV)	0.31	0.29	0.29	0.23	0.22	0.22	0.40	0.36	0.36
5th Percentile	85.29	91.97	94.51	385.71	410.38	414.64	53.68	65.34	68.95
95th Percentile	263.17	264.11	271.79	858.13	874.33	884.12	264.37	256.19	267.24

Sensitivity analysis identifies the uncertainties of the output in a numerical model by assigning different sources of input variables. The Pearson correlation coefficient (r) is the best procedure to measure the association between the dependent and independent variables based on bivariate correlation. The value of r lies between (+)1 and (−)1, where (+)1 indicates a maximum positive linear correlation, 0 means no correlation, and (−)1 indicates the highest negative correlation. Figure 5 shows the correlation scatter plots with different design parameters for brick veneer and precast construction. In the cold temperate zone of Melbourne, the level of insulation *R* has a higher negative association with energy consumption for prefabricated construction (−0.4) than brick veneer (−0.3) building. The other zones also show that the precast concrete structures influence energy reduction strategies more than the traditional ones.

The scatter plot also clarifies the variation in *WWR* has a significant impact on energy consumption irrespective of any building materials and climatic zones, as shown in Figure 5. Higher *WWR* resulted in supplementary energy consumption due to the combined effect of climate. As anticipated, keeping the *WWR* small is a suitable option to improve the thermal efficiency of buildings, and it is more applicable to hot temperate zone (0.98–0.99) than to cold (0.91–0.93). Although it is minimal, similar findings can be drawn concerning the *WWR* effect on energy reduction that performs better for precast concrete.

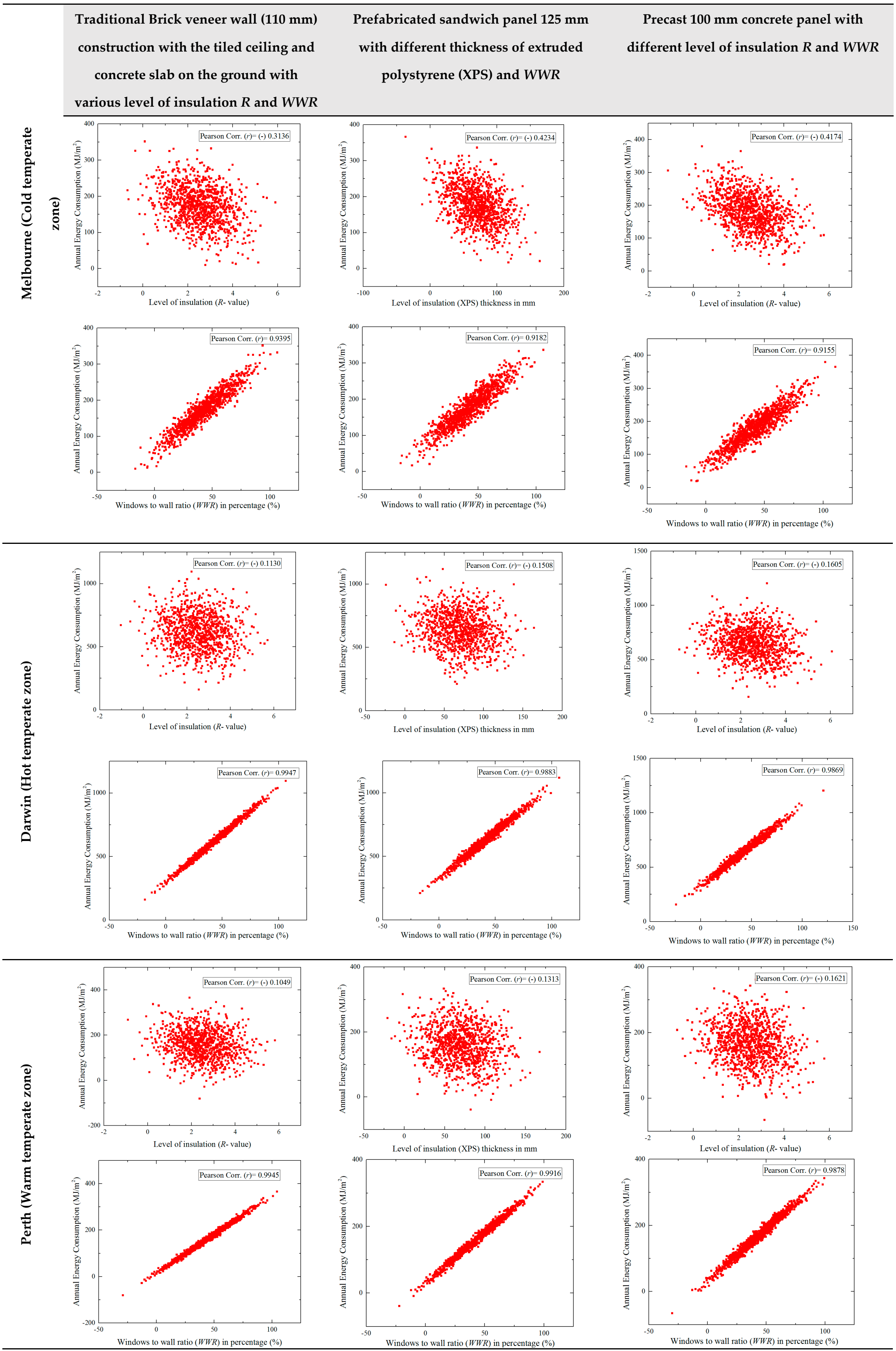

Figure 5. Scatter plots for energy consumption vs. design variables (*R*, *WWR*).

4.4. Life Cycle Assessment of the Entire Building

The entire building life cycle assessment has been performed in the Construction Specification Institute (CSI) standards format. CSI provides a well-organized list of materials divisions to facilitate the associated activities and the relative contribution of each of the divisions. In traditional construction, masonry brick veneer (BV) represents 32.23% of total building mass, but the corresponding representation of CO_2 footprint and energy demand is 22.33% and 22.26%, as shown in Table 5. In prefabricated concrete building construction, the entire building erected with the precast concrete structural panel consists of 84.31% of the total mass. Still, it contributes only 53.27% of total CO_2 emission and 27.25% of the primary energy demand. However, openings and glazing's in division 8 represent approximately 4% of the total mass. Still, their relative contribution to the carbon footprint (14–15%) and embodied energy (16–19%) are very high due to the intensified manufacturing process of glass and aluminium frames. Besides Finishes in division 9, internal wallboard and carpet also result in nearly three times of emission and energy demand as per the proportion of their mass. Moreover, Thermal and Moisture protection in division 7 significantly contributes to the environmental impact relative to the weight. Precise analysis of division 7 materials reveals that insulation materials such as extruded polystyrene (XPS) board have the utmost consequence.

Table 5. Breakdown of total mass, CO_2 emission, and energy demand for traditional and precast concrete construction per the CSI materials division.

Traditional Brick Veneer (BV) Construction				Prefabricated Concrete Panel Construction			
CSI Division	**Total Mass**	**Global Warming Potential ($kgCO_2eq$)**	**Primary Energy Demand (MJ)**	**CSI Division**	**Total Mass**	**Global Warming Potential ($kgCO_2$-eq)**	**Primary Energy Demand (MJ)**
03—Concrete	52,047.82 (34.89%)	14,320.95 (19.54%)	122,952.6 (10.65%)	03—Concrete	142,887.4 (84.31%)	40,487.43 (53.27%)	262,635.8 (27.25%)
Cast-in-place concrete; slab on grade (100 mm)	52,047.82	14,320.95	122,952.6	Precast concrete structural panel (100 mm)	142,887.4	40,487.43	262,635.8
04—Masonry	48,082.9 (32.23%)	16,363.22 (22.33%)	257,041.6 (22.26%)				
Brick (110 mm); generic; grouted	48,082.9	16,363.22	257,041.6				
07—Thermal and Moisture Protection	24,945.31 (16.72%)	11,994.77 (16.37%)	241,479.7 (20.91%)	07—Thermal and Moisture Protection	2489.285 (1.47%)	4932.688 (6.49%)	168,138.9 (17.45%)
Asphalt felt sheet	868.7182	371.9096	28,039.84	Asphalt felt sheet	868.7702	371.9318	28,041.52
Concrete roofing tile	22,454.39	7057.362	73,197.19	Extruded polystyrene (XPS); board	1423.789	4011.965	124,010.9
Extruded polystyrene (XPS); board	1425.206	4015.957	124,134.3	Polyethelene sheet vapor barrier (HDPE)	196.7254	548.7912	16,086.48
Polyethelene sheet vapor barrier (HDPE)	196.9934	549.5387	16,108.39				
08—Openings and Glazing	6498.197 (4.36%)	10,776.22 (14.70%)	188,390.9 (16.31%)	08—Openings and Glazing	6498.197 (3.83%)	10,776.22 (14.18%)	188,390.9 (19.55%)
Door frame; wood	255.1965	1305.936	38,122.41	Door frame; wood	255.1965	1305.936	38,122.41
Door; exterior; wood; solid core	3230.371	4371.319	72,576.51	Door; exterior; wood; solid core	3230.371	4371.319	72,576.51
Glazing; double-pane IGU	1617.17	2424.472	36,185.7	Glazing; double-pane IGU	1617.17	2424.472	36,185.7
Glazing; monolithic sheet	978.075	1231.856	17,323.43	Glazing; monolithic sheet	978.075	1231.856	17,323.43
Window frame; aluminum	417.384	1442.636	24,182.85	Window frame; aluminum	417.384	1442.636	24,182.85
09—Finishes	17,623.79 (11.81%)	19,835.6 (27.06%)	344,990.5 (29.87%)	09—Finishes	17,607.84 (10.39%)	19,811.88 (26.07%)	344,580.5 (35.75%)
Carpet; nylon; generic	3721.684	14,187.54	242,416.7	Carpet; nylon; generic	3716.622	14,168.24	242,087
Wall board; gypsum	13,902.1	5648.061	102,573.8	Wall board; gypsum	13,891.22	5643.639	102,493.5
Grand Total	**149,198**	**73,290.76**	**1,154,855**	**Grand Total**	**169,482.7**	**76,008.21**	**963,746.1**

4.5. Embodied Energy Analysis

This section presents the comparative analysis of embodied energy for different types of precast concrete wall panels with variations in the percentages of fly ashes used in the construction. A breakdown of the environmental impacts of prefabricated wall panels and traditional brick veneer (BV) wall construction has been shown in Table 6. The potential ecological impacts are categorized as acidification (AP), eutrophication (EP), global warming (GWP), ozone depletion (ODP), smog formation (SFP), and primary energy demand (PED). According to the Australian context, primary energy demand considers both sources of energy as non-renewable energy (NRED) and renewable energy (RED). The analysis shows that the external walls built of 100 mm precast concrete panel with the variation of 0%, 25%, 30%, and 50% fly ash contribute to a significant reduction of GWP and PED. The result represents 33.4%, 44.7%, 47.0%, and 54.7% less CO_2 emission than a brick veneer wall for respective fly ash percentages.

Table 6. Embodied energy of conventional and prefabricated wall components.

	Wall Components (Precast Concrete Structural Panel and Brick Veneer)	AP ($kgSO_2$-eq)	EP (kgN-eq)	GWP ($kgCO_2$-eq)	ODP (CFC-11eq)	SFP (kgO_3-eq)	PED (MJ)	NRED (MJ)	RED (MJ)
100 mm structural panel	Precast concrete structural panel; 5000 psi; 0% fly ash: reinforcement 28 kg/m^3	51.52 −30.2%	1.81 57.6%	10,893 33.4%	7.08×10^{-5} −24,567%	702.20 −1.1%	70,663 72.5%	68,724 72.1%	1946 81.7%
	Precast concrete structural panel; 5000 psi; 25% fly ash: reinforcement 28 kg/m^3	41.13 −3.95%	1.62 62.1%	9037 44.7%	5.45×10^{-5} −18,878%	573.10 17.5%	64,709 74.8%	62,750 74.5%	1966 81.5%
	Precast concrete structural panel; 5000 psi; 30% fly ash: reinforcement 28 kg/m^3	39.05 1.29%	1.58 63%	8666 47%	5.14×10^{-5} −17,820%	547.28 21.2%	63,519 75.2%	61,555 75.0%	1971 81.5%
	Precast concrete structural panel; 5000 psi; 50% fly ash: reinforcement 28 kg/m^3	31.81 19.6%	1.53 64.3%	7402 54.7%	3.83×10^{-5} −13,256%	477.75 31.2%	61,901 75.9%	59,892 75.7%	2036 80.9%
125 mm structural panel	Precast concrete structural panel; 5000 psi; 0% fly ash: reinforcement 28 kg/m^3	64.39 −62.7%	2.27 47%	13,615 16.8%	8.85×10^{-5} −30,729%	878 −26.3%	88,316 65.6%	85,893 65.1%	2433 77.1%
	Precast concrete structural panel; 5000 psi; 25% fly ash: reinforcement 28 kg/m^3	51.41 −29.9%	2.03 52.6%	11,296 30.9%	6.81×10^{-5} −23,619%	716 −3.1%	80,875 68.5%	78,427 68.2%	2458 76.9%
	Precast concrete structural panel; 5000 psi; 30% fly ash: reinforcement 28 kg/m^3	48.81 −23.3%	1.98 53.8%	10,832 33.8%	6.43×10^{-5} −22,296%	684 1.6%	79,387 69.1%	76,933 68.8%	2463 76.8%
	Precast concrete structural panel; 5000 psi; 50% fly ash: reinforcement 28 kg/m^3	38.42 −2.8%	1.79 58.2%	8977 45.1%	4.79×10^{-5} −16,592%	555 20.1%	73,434 71.4%	70,960 71.2%	2484 76.7%
Base case	110 mm brick veneer (BV) wall; generic; grouted 2000 kg/m^3	39.57	4.28	16,363	2.87×10^{-7}	695	257,042	246,437	10,663

Similarly, precast concrete panel subsidizes more than BV for reducing primary energy demand, accounting for 72.5%, 74.8%, 75.3%, and 75.9% of less energy demand for consecutive fly ash percentage in 100 mm precast concrete panel. Another precast concrete wall of thickness 125 mm also performs better in reducing CO_2 emissions and energy demand than the traditional one. For example, a 125 mm precast concrete panel with 50% fly ash can reduce up to 45.1% less CO_2 emission and 71.2% less energy demand than brick veneer wall construction. Therefore, the content of embodied energy shows that a significant reduction of environmental impacts is possible through the erection of external walls by either a precast concrete panel of 100 mm or 125 mm with a standard proportion of fly ash mix.

Table 7 shows the comparative analysis of embodied energy between precast concrete floor panels and the traditional floor construction of the concrete slab on the ground (CSOG). The study has been performed with the variation of compressive strength, thickness, fly ashes, and reinforcement in concrete. The enhanced thickness of precast concrete panels contributes to excessive CO_2 emission and energy consumption for manufacturing processes. However, the extent of incorporated fly ashes up to 50% can reduce emissions and energy consumption of the process. For example, the precast concrete panel thickness change from 100 mm to 125 mm results in the additional energy requirements of 24,404 MJ. Nevertheless, by incorporating 50% fly ash, the 125 mm precast concrete panel's primary energy demand is reduced from 120,385 MJ to 100,098 MJ.

Table 7. Embodied energy of concrete panels for fly ash, compressive strength, and reinforcement.

	Floor Components (Precast Concrete Structural Panel and Cast-in-Place Concrete) and Impact Assessment in Terms of kg Equivalent	AP (SO_2-eq)	EP (N-eq)	GWP (CO_2-eq)	ODP (CFC-11eq)	SFP (O_3-eq)	PED (MJ)	NRED (MJ)	RED (MJ)
100 mm structural panel	Precast concrete structural panel; 5000 psi; 0% fly ash: reinforcement 28 kg/m^3	69.98 −9.6%	2.46 38.5%	14,796 −3.3%	9.62×10^{-5} 15.7%	954 −6.1%	95,981 21.9%	93,347 21.6%	2644 30.4%
	Precast concrete structural panel; 5000 psi; 25% fly ash: reinforcement 28 kg/m^3	55.87 12.4%	2.20 45.1%	12,276 14.2%	7.40×10^{-5} 35.1%	778 13.3%	87,894 28.5%	85,233 28.4%	2672 29.7%
	Precast concrete structural panel; 5000 psi; 30% fly ash: reinforcement 28 kg/m^3	53.05 16.8%	2.15 46.4%	11,772 17.8%	6.99×10^{-5} 38.7%	743 17.2%	86,276 29.8%	83,610 29.8%	2677 29.5%
	Precast concrete structural panel; 5000 psi; 50% fly ash: reinforcement 28 kg/m^3	43.21 32.2%	2.08 48.2%	10,054 29.7%	5.21×10^{-5} 54.3%	649 27.7%	84,078 31.6%	81,351 31.7%	2765 27.2%
125 mm structural panel	Precast concrete structural panel,5000 psi; 0% fly ash: reinforcement 28 kg/m^3	87.77 −37.5%	3.09 22.9%	18,558 −29.5%	1.21×10^{-4} −5.7%	1196 −33.1%	120,385 2.0%	117,082 1.7%	3316 12.7%
	Precast concrete structural panel; 5000 psi; 25% fly ash: reinforcement 28 kg/m^3	70.07 −9.82%	2.76 31.1%	15,397 −7.5%	9.28×10^{-5} 18.6%	976 −8.6%	110,241 10.3%	106,904 10.2%	3351 11.8%
	Precast concrete structural panel; 5000 psi; 30% fly ash: reinforcement 28 kg/m^3	66.53 −4.2%	2.70 32.7%	14,765 −3.1%	8.76×10^{-5} 23.2%	932 −3.7%	108,213 11.9%	104,868 12.0%	3358 11.6%
	Precast concrete structural panel; 5000 psi; 50% fly ash: reinforcement 28 kg/m^3	52.38 17.9%	2.44 39.2%	12,236 14.5%	6.53×10^{-5} 42.7%	756 15.8%	100,098 18.5%	96,726 18.8%	3386 10.9%
100 mm cast-in-situ	Cast-in-place concrete; 3000 psi; 0% fly ash; low reinforcement 43.62 kg/m^3	63.81 0%	4.01 0%	14,321 0%	1.14×10^{-4} 0%	898 0%	122,953 0%	119,165 0%	3802 0%
	Cast-in-place concrete; 3000 psi; 25% fly ash; low reinforcement 43.62 kg/m^3	52.12 18.3%	3.79 5.4%	12,234 14.5%	9.58×10^{-5} 16.0%	753 16.1%	116,255 5.4%	112,445 5.6%	3825 −0.6%
	Cast-in-place concrete; 3000 psi; 30% fly ash; low reinforcement 43.62 kg/m^3	49.79 21.9%	3.75 6.4%	11,816 17.4%	9.23×10^{-5} 19.1%	724 19.4%	114,916 6.5%	111,101 6.7%	3829 −0.7%
	Cast-in-place concrete; 3000 psi; 50% fly ash; low reinforcement 43.62 kg/m^3	40.44 36.6%	3.58 10.7%	10,147 29.1%	7.75×10^{-5} 32.0%	608 32.3%	109,558 10.8%	105,724 11.2%	3847 −1.2%
	Cast-in-place concrete; 3000 psi; 50% fly ash; moderate reinforcement 87.24 kg/m^3	44.25 30.6%	3.79 5.5%	11,478 19.8%	8.99×10^{-5} 21.1%	659 26.6%	126,900 −3.2%	120,655 −1.2%	6263 −64.7%
	Cast-in-place concrete; 3000 psi; 50% fly ash; high reinforcement 130.86 kg/m^3	48.05 24.7%	4.00 0.3%	12,808 10.5%	1.02×10^{-4} 10.3%	711 20.9%	144,243 −17.3%	135,586 −13.7%	8678 −128%
100 mm cast-in-situ	Cast-in-place concrete; 5000 psi; 0% fly ash; low reinforcement 44.40 kg/m^3	71.16 −11.5%	2.53 36.8%	15,244 −6.4%	1.00×10^{-4} 11.9%	970 −7.9%	102,144 16.9%	98,616 17.2%	3539 6.9%
	Cast-in-place concrete; 5000 psi; 25% fly ash; low reinforcement 44.40 kg/m^3	57.10 10.5%	2.27 43.3%	12,732 11.0%	7.84×10^{-5} 31.3%	795 11.5%	94,084 23.4%	90,529 24.0%	3566 6.1%
	Cast-in-place concrete; 5000 psi; 30% fly ash; low reinforcement 44.40 kg/m^3	54.29 14.9%	2.22 44.6%	12,230 14.6%	7.42×10^{-5} 34.9%	760 15.4%	92,472 24.7%	88,912 25.3%	3572 6.0%
	Cast-in-place concrete; 5000 psi; 50% fly ash; low reinforcement 44.40 kg/m^3	43.04 32.5%	2.02 49.7%	10,221 28.6%	5.65×10^{-5} 50.4%	620 30.9%	86,024 30.0%	82,442 30.8%	3594 5.4%
	Cast-in-place concrete; 5000 psi; 50% fly ash; moderate reinforcement 88.80 kg/m^3	46.90 26.5%	2.23 44.5%	11,569 19.2%	6.90×10^{-5} 39.4%	672 25.2%	103,593 15.7%	97,567 18.1%	6041 −58.8%
	Cast-in-place concrete; 5000 psi; 50% fly ash; high reinforcement 133.2 kg/m^3	50.75 20.4%	2.44 39.2%	12,917 9.8%	8.16×10^{-5} 28.4%	724 19.4%	121,162 1.4%	112,693 5.4%	8487 −123%
Base	Cast-in-place concrete; 3000 psi; 0% fly ash; low reinforcement 43.62 kg/m^3	63.81	4.01	14,321	1.14×10^{-4}	898	122,953	119,165	3802

The compressive strength of cast-in-place concrete is usually low (3000 psi) as per the concrete design mix at the site. Compressive strength improvement reduces the supplementary energy consumption for concrete production [70,71]. Based on the earlier conducted research on mix design, the high compressive strength of concrete is achievable by reducing water consumption, increasing the fineness modulus (FM) of fine aggregate, and using silica fume [72]. Life cycle analysis shows that reducing manufacturing energy demand for cast-in-place concrete is feasible by upgrading the compressive strength and fly–ash mix. In this study, both precast concrete panels (100 mm, 125 mm) and cast-in-place concrete (100 mm) with 5000 psi compressive strength and 50% fly ash have been testified to which can reduce the primary energy demand by 31.6%, 18.5%, and 30% consecutively compared to the base component.

The embodied energy of cast-in-place concrete is also increased according to reinforcement placement. The use of more reinforcement to gain the tensile strength of the concrete is the main reason for higher emission and energy consumption. The energy-intensive process of manufacturing steel is much higher than concrete production procedures. Fiber-reinforced polymer (FRP) acts as an emerging composite material to improve the performance of reinforced concrete structures (RCC). FRP is widely used in concrete construction as a replacement for reinforcing rebars where corrosion is typical. However, certain disadvantages are associated with FRP composites, such as lower modulus of elasticity, linear elastic brittleness, and weak fire resistance [73]. Structural deflection is higher for FRP's low elastic modulus even at a relatively low-stress level, and FRP's linear-elastic brittle behavior results in the fragile rupture of composite panels. Moreover, FRP composites' are susceptible to temperature, and their mechanical properties deteriorate with increasing temperature. Therefore, reinforcement variation has been considered in this study to identify the possible deviations in impact per design requirements. Low reinforcement (43.62 kg/m^3) in structural concrete causes an energy demand of 109,558 MJ, whereas moderate (87.24 kg/m^3) and high reinforcement (130.86 kg/m^3) increase to 126,900 MJ and 144,243 MJ, respectively. Therefore, the additional reinforcement in concrete is the reason for excessive energy consumption of 15.83% and 31.66% consecutively to the referred low reinforcement concrete.

4.6. Selection of Insulation

Prefabrication has a higher association with the insulation level to reduce the building's energy consumption, as shown in Figure 5. The higher insulation performance can be easily achieved by applying it with precast concrete panels of building fabric. Therefore, the selection of thermal insulation is crucial to use inside the precast sandwich panel or attached with internal cladding. Relative environmental impacts at the embodied phase and weight of varieties of insulation materials are suitable indicators to compare and select a sustainable solution. In this study, life cycle analysis has been performed for different types of insulation to choose the proper insulation applicable to the prefabricated sandwich and concrete panel.

The six most widely used insulation types have been analyzed in this study to obtain environmental impacts, as shown in Table 8. All the insulation materials' thickness has been varied to acquire a specified thermal resistance of R (2.5). Glass fibre board (15–40 kg/m^3) is the most lightweight material among selected insulations; however, excessive energy (206,013 MJ) is consumed for manufacturing. On the contrary, cellulose insulation fibre and boards (30–80 kg/m^3) are much heavier than glass fibre, but the relevant carbon footprint and energy demand are much less than others. Although cellulose insulation is the most environmentally friendly solution, it is restricted in prefabricated sandwich panels due to its weight. Closed cell, spray-applied polyurethane (28–100 kg/m^3) has the highest emissions at its embodied phase due to the fluidized bed application. The density of extruded polystyrene Sheets (XPS) and Expanded Polystyrene Sheets (EPS) varies between 28–45 kg/m^3 and 10–30 kg/m^3 successively. They are light to lift and suitable for use as an insulation layer in sandwich panels. The thickness of consecutive layers XPS (70 mm) and EPS (98 mm) are sufficient to avoid thermal bridges between the prefabricated panels. However, XPS is more resistant to water absorption than EPS. The impact categories of these two types of insulation panels are relatively lower than others except cellulose fiber, especially in terms of CO_2 emissions and primary energy demand. Environmental impacts, density, and thickness for specified thermal resistance are decision-making factors in selecting suitable insulation for the conjugate application of sandwich panels.

Table 8. Embodied energy of insulation materials.

Insulation Level to Achieve *R* (2.5)	AP ($kgSO_2$-eq)	EP (kgN-eq)	GWP ($kgCO_2$-eq)	ODP (CFC-11eq)	SFP (kgO_3-eq)	PED (MJ)	NRED (MJ)	RED (MJ)	Mass (Kg)
Cellulose insulation; blown (52 kg/m^3) (100 mm)	15.5	6.9	2051	-9.11×10^{-9}	92	12,961	10,830	2148	2548
Closed cell; spray-applied polyurethane foam; high density (42 kg/m^3) (100 mm)	29.6	3.3	17,609	2.16×10^{-4}	376	184,952	180,522	4448	2039
Cellulose insulation; boards (70 kg/m^3)	12.1	5.7	2239	1.01×10^{-7}	120	41,258	24,824	16,441	3504
Glass fibre board (20 kg/m^3) (110 mm)	73.4	3.6	12,427	8.52×10^{-4}	812	206,013	191,023	14,994	971
Extruded Polystyrene board (XPS); Pentane foaming agent (29 kg/m^3) (70 mm)	10.9	5.2	4022	2.61×10^{-7}	174	124,319	121,151	3181	1427
Expanded polystyrene (EPS); board (25 kg/m^3) (98 mm)	10.9	4.7	3923	1.51×10^{-4}	224	114,145	112,912	1245	1248

5. Conclusions

The research aims to integrate the operation and embodied phase and to determine the advantages of precast concrete panels over conventional building structures. The results are expressed in terms of thermal efficiency and environmental impact with an overview of the precast panel and relative improvement by incorporating waste (fly ash) to reduce carbon footprint. This study runs energy simulations several times to develop multivariate regression models for climatic diversity and design variables. Advanced regression analysis shows the association of energy consumption with the two main design parameters, window-to-wall ratio (*WWR*) and insulation level (*R*). The research indicates that insulation works more effectively with precast concrete panels to reduce energy consumption than traditional brick cladding, regardless of climate and temperature. Each additional *R*-value of prefabricated elements helps to reduce energy consumption by 21 MJ/m^2 in Melbourne; in contrast to conventional BV, this is 18 MJ/m^2. Multiple coefficients of determination (R^2) explain 97% to 99% of the variation in total energy consumption from design parameters (*WWR*, *R*). An extensive Monte Carlo simulation is also performed using the *@RISK* palisade decision tool to obtain the sensitivity indices and the correlations between the design variables and energy consumption. Therefore, the result recommends using precast concrete panels with smaller *WWRs* for climate-sensitive design. Parametric sensitivity indices provide in-depth design information for selecting precast concrete structures.

This study has conducted the BIM platform's life cycle assessment (LCA) to integrate operational and embodied phases. It determines the relative contribution of each division's materials as per Construction Specifications Institute (CSI). The comparison identifies the potential advantage of precast concrete panels over other materials. The entire precast concrete building represents 84.31% of the total mass but only 53.27% of the CO_2 emissions and 27.25% of the energy demand. In contrast, openings and glazing, including single-glazed aluminium frames, account for only 4% of the total mass. Yet, the relative carbon footprint (14.18%) and energy demand (19.55%) are high due to the intensification of glass frame production. The thermal and moisture protection elements, including insulation effects, are quite large in proportion to their mass. Despite its large mass of precast concrete, it has a potential advantage in terms of durability and reducing emissions. In addition, precast panels provide thermal efficiency regardless of climatic diversity, require minimal maintenance, ensure longevity and provide a significant portion of the precast structure for deconstruction and end-of-life reuse. The study also analyzes variations in design parameters such as compressive strength of concrete, amount of reinforcement, fly ash with different percentages, and lining insulation materials to compensate for the initial embodied energy during its service life for sustainable development.

Comprehensive LCA of the building components shows that the external wall erects of 100 mm precast concrete panel with 50% fly ash can reduce up to 54.7% less CO_2 emission and 75.9% less energy demand than the conventional brick veneer wall of 110 mm. The enhanced thickness of 125 mm precast concrete panel with 50% fly ash reduces emission and energy by 45.1% and 71.2%, respectively. Detailed life cycle analysis recommends the benefit of concrete panels (high mass) for construction applications due to their longer service life and durability. In this study, the reduction of concrete's initial embodied energy has been taken into account by upgrading the compressive strength and incorporating recycled materials like fly ash in different proportions. For example, a 100 mm precast concrete panel with 5000 psi compressive strength and 50% fly ash consumes 31.6% less energy for its manufacture than the base case of 100 mm cast-in-place concrete of 3000 psi. To gain tensile strength of concrete, usage of additional reinforcement such as high and moderate according to the design specification causes excessive embodied energy demand by 15.83% and 31.66%, respectively, than the low reinforcement concrete due to the intensified steel manufacturing process.

In most situations, the lifting capacity of a sandwich wall panel is an essential factor in identifying the critical design load of an insulated precast concrete panel. The study considers detailed impact categories of insulation materials according to the variation in physical properties such as thickness and weight to obtain a specified value of 2.5 of thermal resistance (*R*). The result shows that XPS and EPS boards have lower impacts, are lighter to lift, and even their relative thickness suits avoid thermal bridges by continuation between external and internal panels.

6. Future Scope and Recommendations

The regression analysis findings can be effectively used to predict the energy consumption of the conventional and precast buildings for variation of potential design parameters *WWR* and *R*. Analysis of embodied energy will assist in selecting suitable materials with the least environmental impacts. In this study, calcium-based general Portland cement has been considered to estimate embodied energy, which emits CO_2 when curing. However, emerging magnesite-based cement and other substitutes that absorb CO_2 instead of releasing it can be used in future studies to lessen the embodied energy. Nevertheless, these types of cement are still not currently available commercially in the market.

The article assesses sandwich panels' operational and environmental performance for variations of climatic diversity and widely used insulations. However, experimental studies are required to be performed due to the variations in temperature and densities. Determination of polyester foaming mechanical behavior (shear and compressive strength) is essential from the perspective of bushfire-prone areas like Australia. Linear and non-linear relationships of sandwich panels' strength and modulus elasticity with increased temperature are recommended for future study. A recent study shows polymers such as polyurethane, polyvinylchloride, and others are transformed under the softening process of glass transition at elevated temperatures of 20 °C–200 °C [74]. Strength and shear modulus trend a linear relationship of reduction at enhanced temperature. Changes in thermo-physical properties experienced in polymer materials for densification and shear-stress distribution at different loading and temperature are now a prime concern to be studied for sandwich panels.

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References

1. Karlsson, I.; Rootzén, J.; Johnsson, F. Reaching net-zero carbon emissions in construction supply chains–Analysis of a Swedish road construction project. *Renew. Sustain. Energy Rev.* **2020**, *120*, 109651. [CrossRef]
2. Sandanayake, M.; Lokuge, W.; Zhang, G.; Setunge, S.; Thushar, Q. Greenhouse gas emissions during timber and concrete building construction—A scenario based comparative case study. *Sustain. Cities Soc.* **2018**, *38*, 91–97. [CrossRef]
3. Vilches, A.; Garcia-Martinez, A.; Sanchez-Montanes, B. Life cycle assessment (LCA) of building refurbishment: A literature review. *Energy Build.* **2017**, *135*, 286–301. [CrossRef]
4. Azhar, S.; Carlton, W.A.; Olsen, D.; Ahmad, I. Building information modeling for sustainable design and LEED® rating analysis. *Autom. Constr.* **2011**, *20*, 217–224. [CrossRef]
5. Kuznik, F.; David, D.; Johannes, K.; Roux, J.-J. A review on phase change materials integrated in building walls. *Renew. Sustain. Energy Rev.* **2011**, *15*, 379–391. [CrossRef]
6. Gregory, K.; Moghtaderi, B.; Sugo, H.; Page, A. Effect of thermal mass on the thermal performance of various Australian residential constructions systems. *Energy Build.* **2008**, *40*, 459–465. [CrossRef]
7. Beckett, C.; Ciancio, D. A review of the contribution of thermal mass to thermal comfort in rammed earth structures. In Proceedings of the 2nd International Conference on Sustainable Built Environment, Kandy, Sri Lanka, 14–16 December 2012.
8. Aditya, L.; Mahlia, T.; Rismanchi, B.; Ng, H.; Hasan, M.; Metselaar, H.; Muraza, O.; Aditiya, H. A review on insulation materials for energy conservation in buildings. *Renew. Sustain. Energy Rev.* **2017**, *73*, 1352–1365. [CrossRef]
9. Zhu, L.; Hurt, R.; Correia, D.; Boehm, R. Detailed energy saving performance analyses on thermal mass walls demonstrated in a zero energy house. *Energy Build.* **2009**, *41*, 303–310. [CrossRef]
10. Tushar, Q.; Zhang, G.; Bhuiyan, M.A.; Giustozzi, F.; Navaratnam, S.; Hou, L. An optimized solution for retrofitting building façades: Energy efficiency and cost-benefit analysis from a life cycle perspective. *J. Clean. Prod.* **2022**, *376*, 134257. [CrossRef]
11. Uriarte, A.; Garai, I.; Ferdinando, A.; Erkoreka, A.; Nicolas, O.; Barreiro, E. Vacuum insulation panels in construction solutions for energy efficient retrofitting of buildings. *Two Case Stud. Spain Swed. Energy Build.* **2019**, *197*, 131–139.
12. Shirazi, A.; Ashuri, B. Embodied Life Cycle Assessment (Lca) Comparison OF Residential Building Retrofit Measures in Atlanta. *Build. Environ.* **2020**, *171*, 106644. [CrossRef]
13. Silva, R.; de Brito, J.; Dhir, R. Availability and processing of recycled aggregates within the construction and demolition supply chain: A review. *J. Clean. Prod.* **2017**, *143*, 598–614. [CrossRef]
14. Tushar, Q.; Bhuiyan, M.A.; Zhang, G.; Maqsood, T. An integrated approach of BIM-enabled LCA and energy simulation: The optimized solution towards sustainable development. *J. Clean. Prod.* **2020**, *289*, 125622. [CrossRef]
15. Insulation Council of Australia and New Zealand. Insulation Handbook, I. Part 1: Thermal Performance—Version 3, Total R-Value Calculation for Typical Building Applications. December 2016. Available online: http://icanz.org.au/wp-content/uploads/2016/12/Insulation-Handbook-Part-1-Thermal-Performance-Version-3-December-2016.pdf (accessed on 1 October 2022).
16. Ding, K.W.; Wang, G.; Yin, W.Y. Application of composite sandwich panels in construction engineering. *Appl. Mech. Mater.* **2013**, *291–294*, 1172–1176. [CrossRef]
17. Bhatti, A.Q. Application of dynamic analysis and modelling of structural concrete insulated panels (SCIP) for energy efficient buildings in seismic prone areas. *Energy Build.* **2016**, *128*, 164–177. [CrossRef]
18. Balaji, P.; Selvan, S.A. Performance evaluation of ferro cement sandwich wall panels with different infills. *Perform. Eval.* **2018**, *5*, 1518–1524.
19. Williamson, T. Assessing the effectiveness for thermal mass in the building envelop. In Proceedings of the Building Simulation 2011: 12th Conference of International Building Performance Simulation Association, Sydney, NSW, Australia, 14–16 November 2011; pp. 1655–1661.
20. Huang, Q.; Hamed, E.; Gilbert, R. *Experimental and Numerical Investigation of the Flexural Behaviour of Composite Prefabricated Concrete Sandwich Panels, ACMSM25*; Springer: Berlin/Heidelberg, Germany, 2020; pp. 123–130.
21. Kunič, R. Forest-based bioproducts used for construction and its impact on the environmental performance of a building in the whole life cycle. In *Environmental Impacts of Traditional and Innovative Forest-Based Bioproducts*; Springer: Berlin/Heidelberg, Germany, 2016; pp. 173–204.
22. Thomas, M. *Optimizing the Use of Fly Ash in Concrete*; Portland Cement Association: Skokie, IL, USA, 2007.
23. Seto, K.E.; Churchill, C.J.; Panesar, D.K. Influence of fly ash allocation approaches on the life cycle assessment of cement-based materials. *J. Clean. Prod.* **2017**, *157*, 65–75. [CrossRef]

24. Boafo, F.E.; Kim, J.-H.; Kim, J.-T. Performance of modular prefabricated architecture: Case study-based review and future pathways. *Sustainability* **2016**, *8*, 558. [CrossRef]
25. Luo, T.; Xue, X.; Tan, Y.; Wang, Y.; Zhang, Y. Exploring a body of knowledge for promoting the sustainable transition to prefabricated construction. *Eng. Constr. Archit. Manag.* **2020**, *28*, 2637–2666. [CrossRef]
26. Islam, H.; Zhang, G.; Setunge, S.; Bhuiyan, M.A. Life cycle assessment of shipping container home: A sustainable construction. *Energy Build.* **2016**, *128*, 673–685. [CrossRef]
27. Rosso, F.; Golasi, I.; Castaldo, V.L.; Piselli, C.; Pisello, A.L.; Salata, F.; Ferrero, M.; Cotana, F.; de Lieto Vollaro, A. On the impact of innovative materials on outdoor thermal comfort of pedestrians in historical urban canyons. *Renew. Energy* **2018**, *118*, 825–839. [CrossRef]
28. Enescu, D. A review of thermal comfort models and indicators for indoor environments. *Renew. Sustain. Energy Rev.* **2017**, *79*, 1353–1379. [CrossRef]
29. Ascione, F.; Bianco, N.; de Stasio, C.; Mauro, G.M.; Vanoli, G.P. Multi-stage and multi-objective optimization for energy retrofitting a developed hospital reference building: A new approach to assess cost-optimality. *Appl. Energy* **2016**, *174*, 37–68. [CrossRef]
30. Islam, H.; Bhuiyan, M.; Tushar, Q.; Navaratnam, S.; Zhang, G. Effect of Star Rating Improvement of Residential Buildings on Life Cycle Environmental Impacts and Costs. *Buildings* **2022**, *12*, 1605. [CrossRef]
31. JHygh, S.; DeCarolis, J.F.; Hill, D.B.; Ranjithan, S.R. Multivariate regression as an energy assessment tool in early building design. *Build. Environ.* **2012**, *57*, 165–175.
32. O'Leary, T. Industry Adaption to NatHERs 6 Star Energy Regulations and Energy Performance Disclosure Models for Housing. Ph.D. Thesis, University of South Australia, Port Augusta, SA, Australia, December 2016. Available online: https://rest.neptune-prod.its.unimelb.edu.au/server/api/core/bitstreams (accessed on 1 October 2022).
33. Rajagopalan, P.; Wong, J.P.; Andamon, M.M. Building performance simulation in the built environment education: Experience from teaching two disciplines. In Proceedings of the 50th International Conference of the Architectural Science Association, Adelaide, Australia, 7–9 December 2016; pp. 359–368.
34. Bruhns, A.; Deurveilher, G.; Roy, J.-S. A non linear regression model for mid-term load forecasting and improvements in seasonality. In Proceedings of the 15th Power Systems Computation Conference, Liege, Belgium, 22–26 August 2005; pp. 22–26.
35. Tushar, Q.; Bhuiyan, M.A.; Zhang, G. Energy simulation and modeling for window system: A comparative study of life cycle assessment and life cycle costing. *J. Clean. Prod.* **2021**, *330*, 129936. [CrossRef]
36. Catalina, T.; Virgone, J.; Blanco, E. Development and validation of regression models to predict monthly heating demand for residential buildings. *Energy Build.* **2008**, *40*, 1825–1832. [CrossRef]
37. Li, D.; Wong, S.L.; Cheung, K.L. Energy performance regression models for office buildings with daylighting controls. *Proc. Inst. Mech. Eng. Part A J. Power Energy* **2008**, *222*, 557–568. [CrossRef]
38. Carlo, J.; Lamberts, R. Development of envelope efficiency labels for commercial buildings: Effect of different variables on electricity consumption. *Energy Build.* **2008**, *40*, 2002–2008. [CrossRef]
39. Bansal, N.K.; Bhattacharya, A. Parametric equations for energy and load estimations for buildings in India. *Appl. Therm. Eng.* **2009**, *29*, 3710–3715. [CrossRef]
40. Lam, J.C.; Hui, S.C.; Chan, A.L. Regression analysis of high-rise fully air-conditioned office buildings. *Energy Build.* **1997**, *26*, 189–197. [CrossRef]
41. JLam, C.; Wan, K.K.; Liu, D.; Tsang, C. Multiple regression models for energy use in air-conditioned office buildings in different climates. *Energy Convers. Manag.* **2010**, *51*, 2692–2697.
42. Iman, R.L. *Latin Hypercube Sampling*; Wiley: Hoboken, NJ, USA, 2014.
43. Tushar, Q.; Santos, J.; Zhang, G.; Bhuiyan, M.A.; Giustozzi, F. Recycling waste vehicle tyres into crumb rubber and the transition to renewable energy sources: A comprehensive life cycle assessment. *J. Environ. Manag.* **2022**, *323*, 116289. [CrossRef]
44. Paxton, P.; Curran, P.J.; Bollen, K.A.; Kirby, J.; Chen, F. Monte Carlo experiments: Design and implementation. *Struct. Equ. Modeling* **2001**, *8*, 287–312. [CrossRef]
45. Landau, D.P.; Binder, K. *A Guide to Monte Carlo Simulations in Statistical Physics*; Cambridge University Press: Cambridge, UK, 2014.
46. Feizizadeh, B.; Jankowski, P.; Blaschke, T. A GIS based spatially-explicit sensitivity and uncertainty analysis approach for multi-criteria decision analysis. *Comput. Geosci.* **2014**, *64*, 81–95. [CrossRef]
47. Sun, Y.; Gu, L.; Wu, C.J.; Augenbroe, G. Exploring HVAC system sizing under uncertainty. *Energy Build.* **2014**, *81*, 243–252. [CrossRef]
48. Spitz, C.; Mora, L.; Wurtz, E.; Jay, A. Practical application of uncertainty analysis and sensitivity analysis on an experimental house. *Energy Build.* **2012**, *55*, 459–470. [CrossRef]
49. Tushar, Q.; Bhuiyan, M.; Zhang, G.; Sandanayake, M. Correlation of Building Parameters with Energy Reduction. In Proceedings of the 2018 5th Asia-Pacific World Congress on Computer Science and Engineering (APWC on CSE), Nadi, Fiji, 10–12 December 2018; pp. 116–120.
50. Cabeza, L.F.; Rincón, L.; Vilariño, V.; Pérez, G.; Castell, A. Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: A review. *Renew. Sustain. Energy Rev.* **2014**, *29*, 394–416. [CrossRef]
51. Huntzinger, D.N.; Eatmon, T.D. A life-cycle assessment of Portland cement manufacturing: Comparing the traditional process with alternative technologies. *J. Clean. Prod.* **2009**, *17*, 668–675. [CrossRef]

52. Zhang, G.; Sandanayake, M.; Setunge, S.; Li, C.; Fang, J. Selection of emission factor standards for estimating emissions from diesel construction equipment in building construction in the Australian context. *J. Environ. Manag.* **2017**, *187*, 527–536. [CrossRef]
53. Notarnicola, B.; Sala, S.; Anton, A.; McLaren, S.J.; Saouter, E.; Sonesson, U. The role of life cycle assessment in supporting sustainable agri-food systems: A review of the challenges. *J. Clean. Prod.* **2017**, *140*, 399–409. [CrossRef]
54. Peng, C. Calculation of a building's life cycle carbon emissions based on Ecotect and building information modeling. *J. Clean. Prod.* **2016**, *112*, 453–465. [CrossRef]
55. Ji, Y.; Qi, K.; Qi, Y.; Li, Y.; Li, H.X.; Lei, Z.; Liu, Y. BIM-based life-cycle environmental assessment of prefabricated buildings. *Eng. Constr. Archit. Manag.* **2020**, *27*, 1703–1725. [CrossRef]
56. Yang, X.; Hu, M.; Wu, J.; Zhao, B. Building-information-modeling enabled life cycle assessment, a case study on carbon footprint accounting for a residential building in China. *J. Clean. Prod.* **2018**, *183*, 729–743. [CrossRef]
57. Wastiels, L.; Decuypere, R. Identification and comparison of LCA-BIM integration strategies. In *IOP Conference Series: Earth and Environmental Science*; IOP Publishing: Bristol, UK, 2019; p. 012101.
58. Meex, E.; Hollberg, A.; Knapen, E.; Hildebrand, L.; Verbeeck, G. Requirements for applying LCA-based environmental impact assessment tools in the early stages of building design. *Build. Environ.* **2018**, *133*, 228–236. [CrossRef]
59. Hu, Z.-Z.; Zhang, X.-Y.; Wang, H.-W.; Kassem, M. Improving interoperability between architectural and structural design models: An industry foundation classes-based approach with web-based tools. *Autom. Constr.* **2016**, *66*, 29–42. [CrossRef]
60. Böhms, H.; Plokker, W.; Charvier, B.; Madrazo, L.; Sicilia, A. IntUBE energy information integration platform. In Proceedings of the 8th European Conference on Product and Process Modelling (ECPPM), Cork, Ireland, 12–14 September 2010; pp. 339–344.
61. Al-Ghamdi, S.G.; Bilec, M.M. Green building rating systems and whole-building life cycle assessment: Comparative study of the existing assessment tools. *J. Archit. Eng.* **2017**, *23*, 04016015. [CrossRef]
62. Najjar, M.; Figueiredo, K.; Palumbo, M.; Haddad, A. Integration of BIM and LCA: Evaluating the environmental impacts of building materials at an early stage of designing a typical office building. *J. Build. Eng.* **2017**, *14*, 115–126. [CrossRef]
63. Santos, R.; Costa, A.A. *Information Integration and Interoperability for BIM-Based Life-Cycle Assessment, Integrating Information in Built Environments*; Routledge: London, UK, 2017; pp. 91–108.
64. Bueno, C.; Fabricio, M.M. Comparative analysis between a complete LCA study and results from a BIM-LCA plug-in. *Autom. Constr.* **2018**, *90*, 188–200. [CrossRef]
65. GhaffarianHoseini, A.; Zhang, T.; Nwadigo, O.; GhaffarianHoseini, A.; Naismith, N.; Tookey, J.; Raahemifar, K. Application of nD BIM Integrated Knowledge-based Building Management System (BIM-IKBMS) for inspecting post-construction energy efficiency. *Renew. Sustain. Energy Rev.* **2017**, *72*, 935–949. [CrossRef]
66. Mora, T.D.; Bolzonello, E.; Peron, F.; Carbonari, A. Integration of LCA tools in BIM toward a regenerative design. In Proceedings of the PLEA 2018 Hong Kong, Honk Kong, China, 10–12 December 2018; pp. 341–346.
67. Lu, W.; Yuan, H. Investigating waste reduction potential in the upstream processes of offshore prefabrication construction. *Renew. Sustain. Energy Rev.* **2013**, *28*, 804–811. [CrossRef]
68. Tushar, Q.; Bhuiyan, M.A.; Zhang, G.; Maqsood, T.; Tasmin, T. Application of a harmonized life cycle assessment method for supplementary cementitious materials in structural concrete. *Constr. Build. Mater.* **2022**, *316*, 125850. [CrossRef]
69. Martínez-Rocamora, A.; Solís-Guzmán, J.; Marrero, M. LCA databases focused on construction materials: A review. *Renew. Sustain. Energy Rev.* **2016**, *58*, 565–573. [CrossRef]
70. Yaragal, S.C.; Teja, D.C.; Shaffi, M. Performance studies on concrete with recycled coarse aggregates. *Adv. Concr. Constr.* **2016**, *4*, 263. [CrossRef]
71. Yagoob, N.M.A.E.R. *Design of High Compressive Strength Concrete Mix without Additives*; Sudan University of Science & Technology: Kharthum, Sudan, 2017.
72. GAbreu, B.d.; Costa, S.M.M.; Gumieri, A.G.; Calixto, J.M.F.; França, F.C.; Silva, C.; Quinõnes, A.D. Mechanical properties and microstructure of high performance concrete containing stabilized nano-silica. *Matéria* **2017**, *22*. [CrossRef]
73. Lin, X.; Zhang, Y.; Pathak, P. *Nonlinear Finite Element Analysis of Composite and Reinforced Concrete Beams*; Woodhead Publishing: Thorston, UK, 2019.
74. Mazzuca, P.; Firmo, J.P.; Correia, J.R.; Garrido, M. Mechanical behaviour in shear and compression of polyurethane foam at elevated temperature. *J. Sandw. Struct. Mater.* **2022**, *24*, 1429–1448. [CrossRef]