VERTICAL EXTENSIONS: TECHNICAL CHALLENGES AND CARBON IMPACT

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A project report submitted in partial fulfilment of the requirements for the award of Bachelor of Engineering (Honours) Civil Engineering

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DECLARATION

I hereby declare that this project report is based on my original work except for citations and quotations which have been duly acknowledged. I also declare that it has not been previously and concurrently submitted for any other degree or award at UTAR or other institutions.

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APPROVAL FOR SUBMISSION

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ABSTRACT

The population in the major cities is growing steadily and is anticipated to continue to rise. This indicates a greater need for living spaces in city centers. One option that has been considered is extending the building vertically, which utilises the remaining building area of the existing building. This research aimed to investigate the technical challenges and carbon impact associated with vertical extensions of the existing building. The objectives of this research are to identify the typical considerations, design approach and structural performance of the vertical extension and to compare the vertical extension with the demolition and reconstruction of the structure in terms of carbon footprint and environmental impacts. In this research, the existing building is modelled and analysed using SCIA Engineer and then later transformed into an extended building. The existing building of G + 11, with two levels of basement car park was vertically extended to G + 13. Findings revealed that the existing structural elements are able to sustain the additional loads from two extended storeys without the need for structural reinforcement. The model expansion causes the increase in overall support reactions mainly because the structural elements are required to bear a greater self-weight of the building. The technical challenges associated with vertical extension include the availability of information on the existing building, actual conditions of the building, constructability and installation methods, installation of building services, building retrofitting, fire protection requirements, and accessibility issues. Hawkins\Brown Emissions Reduction Tool (H\B:ERT) in Revit and IStructE guide are the helpful tools to assess carbon emissions throughout the building's lifecycle. The vertical extension appears to be a more carbon-efficient option as compared to demolition and reconstruction. The carbon emissions arising from demolition and rebuilding are 11006.218 tCO2e, significantly higher than vertical extension (386.123 tCO_2e) whereas reconstruction accounted for 10891.510 tCO_2e emissions, contributing to 99 % of the total emissions.

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LIST OF SYMBOLS / ABBREVIATIONS

C_{pe}	external pressure coefficient
C_{pi}	internal pressure coefficient
E	elastic modulus, MPa
f_{ck}	characteristic compressive strength, MPa
f_{tk}	maximum tensile stress, MPa
f_{yk}	characteristic yield strength, MPa
G	shear modulus, MPa
GIA	gross internal area, m^2
g_k	permanent load, kN/m^2
q_k	imposed load, kN/m^2
R_z	reaction force, kN

B	basement floor
BIM	building information modelling
CC	construction coefficient, %
CFRP	carbon fibre reinforced polymer
CFS	cold-formed steel
CLT	cross-laminated timber
CO_2	carbon dioxide
C&S	civil and structural
CO_2e	carbon dioxide equivalent
COL	column
C&S	civil and structural
EC	embodied carbon, tCO_2e
ECF	embodied carbon factor, $kg/CO_2e/kg$ material
ELC	end life coefficient, %
FRP	fiber reinforced polymer
G	ground floor
H\B:ERT	Hawkins\Brown Emissions Reduction Tool
LCA	life cycle analysis
N	node
RC	reinforced concrete

RHS	rectangular hollow section
SCORS	structural carbon rating scheme
SDG	sustainable development goals
SHS	square hollow section
TC	transport coefficient, %
ULS	ultimate limit state
VE	vertical extensions
W	overall material weight, tons
WF	waste factor
Wt	weight of the material, tons
WR	material waste rate, %

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CHAPTER 1

INTRODUCTION

1.1 General Introduction

Economic development and urbanisation are the primary causes of change in today's world. The population in the major cities is increasing steadily, and it is projected to continue to rise in the future. The United Nations (2008) states that almost 70% of the world's population will be living in cities by 2050. This indicates a greater need for residential buildings or apartments in city centres. According to Balaras et al. (2005), building affects the environment, starting from the production of raw materials, construction, maintenance and refurbishment to the emission of hazardous chemicals throughout the buildings' life. In fact, UNEP (2009) claimed that buildings account for more than one-third of greenhouse gas emissions and 40 % of world energy consumption in both developed and developing nations. Considering the growing demand and increasing concerns on sustainability issues, the retrofitting of the existing building has attracted many researchers (Artés, Wadel and Martí, 2017; Papageorgiou, 2016). In that case, the existing structure can be extended horizontally or vertically to create more urban living space.

From an environmental viewpoint, vertical extension is considered a helpful approach compared to a horizontal extension. This is because vertical extension may add living space without requiring more land than horizontal extension. In some cases, where there are limitations on land use, the current practices are to demolish the existing structure and construct a new building that can meet the population demand. Vertical extension is a more viable solution as it can increase the city's density by introducing additional floors without massive demolition of the existing structure and material consumption. Furthermore, another essential feature of the vertical extension is that it can reuse previously developed land and resources such as roads, telecommunications, sewage systems, and etc. The vertical extension also enables full utilization of the unrevealed capacity in the existing building, which is vital in meeting the industry's net-zero carbon objective.

Apart from the benefits mentioned earlier, the vertical extension can be said to be an approach toward sustainable urban development in attaining the United Nations Sustainable Development Goals (SDG):

i. SDG 12 and 13: Responsible consumption, such as building reuse which, may mitigate carbon emissions and therefore have a direct effect on the climate emergency.
ii. SDG 7 and 10: Extensions may provide income to maintain or improve the existing building's energy performance.
iii. SDG 11: Extensions increase the urban's density which helps to prevent development on greenfield locations and decrease the need for infrastructure, resulting in more sustainable cities and towns.

Vertical extension, however, is often characterized by considerable uncertainties and risks due to lack of knowledge and its technical challenges. In the case where vertical extensions are poorly planned and constructed, the adverse consequences can be the collapse of the building and loss of lives. Therefore, there is a need to develop a better understanding on the concept of vertical extension before the design process.

1.2 Importance of the Study

This study provides necessary knowledge on the structural considerations and technical challenges of vertical extensions. This study is essential to evaluate potential in extending the building vertically from the perspective of a structural engineer. The outcome of this research is vital to verify the possibility of reusing the building, which contributes to a more sustainable built environment as opposed to demolition and new construction.

1.3 Problem Statement

Research and existing case studies suggested that vertical extension can be an alternative to demolition and new construction in meeting the demand due to the densifying urban. However, vertical extension is associated with several structural and technical challenges that have yet to be addressed. Although vertical extensions had been done in some cases, the opportunities on the structural design and the implications of vertical extension are yet to be explored. Moreover, there are limited research studies on the selection of different extension materials, and none of the studies evaluates the influence of vertical extensions on the environment. Thus, in order to verify the sustainability of the vertical extension, further consideration was taken to compare the environmental impact of demolition and new construction to a vertical extension.

1.4 Aim and Objectives

This research aims to investigate the technical challenges and carbon impact associated with vertical extensions of the existing building. The specific objectives of this research are as follows:

i. To identify the typical considerations, design approach and structural performance of the vertical extension.
ii. To evaluate the environmental impact of the vertical extension and compare it with the demolition and reconstruction of the structure in terms of carbon emissions.

1.5 Scope and Limitation of the Study

The scope of this research is to simulate and perform a preliminary structural analysis for the extension of the existing building with two additional storeys using SCIA Engineer software. The main focuses are to validate the feasibility of vertical extension. The scope of this study also includes the comparative study of carbon footprint resulting from the two proposed scenarios, namely vertical extension of the existing building and demolition and reconstruction. Revit software and IStructE guide are adopted in the estimation of embodied carbon.

The current study, however, is subjected to some limitations that might be considered in future research. The primary limitation is that this research focuses on the structural aspect, and the integration of building services was not included in this study. Second, only upward vertical extension was covered in this research, and the opportunities for downward extension and strengthening were not evaluated. Another concern is that the costs of the building were not considered in defining the optimal vertical extension. Besides, the condition of the existing building could not be verified as the site inspections and surveys were impossible to be carried out by the author. The structural system of the existing building is assumed to be in good condition, which might not be true in actual cases. Furthermore, the detailed design and the installation methods of the extension modules were not covered in the present research. Lastly, the carbon emission assessment represents a preliminary estimation, and only typical structural materials were considered in the study.

1.6 Contribution of the Study

The outcome of this study provides useful insights into the structural considerations and technical challenges associated with vertical extension, which help the reader establish a more efficient development and construction process for vertical extension projects in the future. The findings served as a starting point in examining the possibilities of vertical extension as a lower-carbon alternative to demolition and reconstruction.

1.7 Outline of Report

Chapter 1: Introduction

This chapter provides a general introduction to vertical extension. In addition, the importance of the study, problem statement, aim and objectives, and scope and limitations of this study were included in this chapter.

Chapter 2: Literature Review

The existing case studies and research for vertical extensions were thoroughly reviewed. The typical structural considerations and common strategies for vertical extensions were discussed in this chapter.

Chapter 3: Methodology and Workplan

This chapter describes the detailed procedures of this study, from planning to simulation using SCIA Engineer software and evaluation of carbon footprint.

Chapter 4: Results and Discussion

This chapter presents linear analysis results of the existing and extended building models. The technical challenges associated with vertical were presented and discussed in detail. Besides that, the carbon impact of vertical extension, as well as demolition and reconstruction, were compared and discussed.

Chapter 5: Conclusions and Recommendations

This chapter concludes the analysis and discussion of the findings related to the vertical extension and carbon impact. Furthermore, several suggestions were provided to enhance the shortcomings of the present study in preparation for the future study.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

In this chapter, the typical structural considerations associated with vertical extension were discussed. Several existing case studies of the vertical extension were reviewed and analysed. Lastly, common strategies or technical solutions for vertical extension were identified and described in this section.

2.2 Structural Considerations Associated with Vertical Extensions

The technical challenges pertinent to vertical extensions are essential factors that influence the feasibility of a vertical extension. The typical structural considerations that must be considered throughout the design development include the desk study of the original building, structural evaluation of the existing building conditions and determination of the new load due to the extension.

2.2.1 General Considerations

A comprehensive desk study is necessary to understand the original design better so that the structural design can be carried out correctly. The primary purposes are to analyse the structural load carrying capacity and understand its load paths (Papageorgiou, 2016; E and Memari, 2014). Valuable information on the original design, construction, and modifications may be obtained by reviewing the existing records, such as the architectural and structural drawings, detailing, material specifications, and reports with design calculations. These documents may be retrieved from the local authorities or building owners.

Structural analysis is required to determine the structural and spare capacity for structural engineers to determine whether the existing structure is suitable for extension and how many stories can be added and to identify the need for modifications or strengthening works. The initial structural investigation process depends mainly on the availability and reliability of existing information. Researchers (Ali, 2014; Norell, Stehn and Engström,

2020) point out that the lack of information about the design of the existing structure, layout, and operating facilities are the common problems encountered in an extension project. Because of this, various tests, structural inspections, opening-up, and methods can be used to determine the existing structure's technical features (Papageorgiou, 2016). The test and methods are applicable when the aforementioned information is unavailable and helpful in verifying critical aspects of the information available as the design documents should not be relied upon entirely.

Besides, special attention must be paid to the relevant codes of practices and standards used at the time the building was constructed. The code of practice sets the rules and criteria that serve as a guideline to be used with the analysis and design methods, materials and building construction methods. A check of the design based on the out-of-date codes used at the time may help indicate the adequacy of structure and whether the original design was carried out appropriately (The Institution of Structural Engineers, 2010). However, it is worth mentioning that such codes or standards may contain criteria and information that is no longer considered appropriate. As the codes of practice are often matured and updated over the years, it is sometimes useful to compare those code requirements used when the building was constructed with the latest design codes. In case there are differences in standards, the main focus should be on the adequacy of the structure and whether there is a need for modifications.

2.2.2 Existing Building Condition

The building condition assessment is significant to identify any modifications from the original design, the accuracy of the desk study, the level of maintenance of the structure, and any defects that might affect the stability and durability of the existing system (Fernandez, 2020). If defects or damages are identified, it is essential to determine the causes behind and evaluate the possible structural risks. The critical areas that should be considered include as-built construction, material properties, structural frame damage, corrosion, reinforcement, modification to the structure or installation of heavy mechanical equipment without engineering review, unusual defects, foundation settlement, cracking, and unusual deformation (Schwinger, 2007).

This can be done through inspections, surveys, or local opening-up. In addition, there are various types of tests to identify the structural systems' mechanical properties, strength, and quality. The standard methods adopted for building assessment have been reviewed and summarized in Table 2.1 below.

Table 2.1: Testing Techniques to Investigate the Strength of Existing Structure (Papageorgiou, 2016; Flohrer, 2010).

Test Tasks	Testing Techniques	Aim of Test
Concrete compressive strength	• Rebound/ Schmidt hammer • Destructive testing of drilling cores	Classification of concrete based on compressive strength grades
Surface tensile strength	• Tensile strength test	Applying composite layers on old concrete surfaces
Concrete cover, determination of the reinforcement's diameter	• Cover meter • Radar (deep reinforcement)	Evaluate the durability and load-bearing capacity
Position and alignment of reinforcement	• Cover meter • Radar • Radiography	Evaluate the durability and load-bearing capacity
Detection of flaws inside the concrete, structural modifications	• Radar • Ultrasonic echo • Impact-echo	Evaluate the homogeneity of massive elements
Determination of the thickness of the structure, depth of installation parts or defects	• Impact-echo • Ultrasonic echo • Radar	Unilaterally accessible structural components, displacement bodies inside the concrete, and steel installation parts. Detect insulating layers or separating layers, as well as multilayer components
Layer composition of wall and floor	• Radar and further minor destructive test such as endoscopy	For the large-scale inventory-taking inside the building diagnosis

Table 2.1 (Continued)

The moisture content of the elements	• Microwaves, radar, capacitive methods	Determine the moisture content of building materials and elements
Location of tendons (lateral position, depth position)	• Radar	Reliable identification of tendons as a pre-study prior to other tendons investigation or repair work
Compaction faults inside tendons of post-tensioning	• Ultrasonic echo	Contribute to the study of the stability of prestressed concrete
Active corrosion of reinforcement	• Potential difference method	Evaluate the durability and the stability
Cracks of tension wire	• Magnetic field method	Evaluation of prestressed concrete for potential tension wires cracks
Glued laminated timber beams	• Ultrasonic echo	Investigation of glulam beams concerning structure or delaminations

2.2.3 Imposed Load

Vertical extensions correspond to the addition of one or more new floors to the host building. The additional floor or new services may increase original design loadings. Therefore, it is essential to justify the new loadings during a vertical extension.

A favourable scenario for the renovation of existing buildings is no net increase in the original design loads. This is to ensure that the additional storeys can be added with minimal physical intervention. Within this context, it is likely to reduce the loading by comparing the live load on the existing floors against the current codes of practice to determine whether extensive allowances have historically been adopted (Fernandez, 2021). Apart from that, the removal of elements such as existing roof finishes, ceilings, services, upper slabs or non-load bearing walls could help in balancing the extracted load and superimposed load (Artés, Wadel and Martí, 2017). This allows us to estimate the allowable weight that can be introduced. Unfortunately, the extracted weight is often insufficient to compensate for the weight of additional floors, causing an increase in the imposed loads that might exceed the load-bearing capacity of existing structures. Therefore, it is necessary to determine the total new design loading, compare it with the total existing loads and assess the load bearing capacity of the existing foundation and structural members to identify the need to reinforce or modify. The assessment process for the new design loading against the existing load-bearing capacity is illustrated in Figure 2.1.

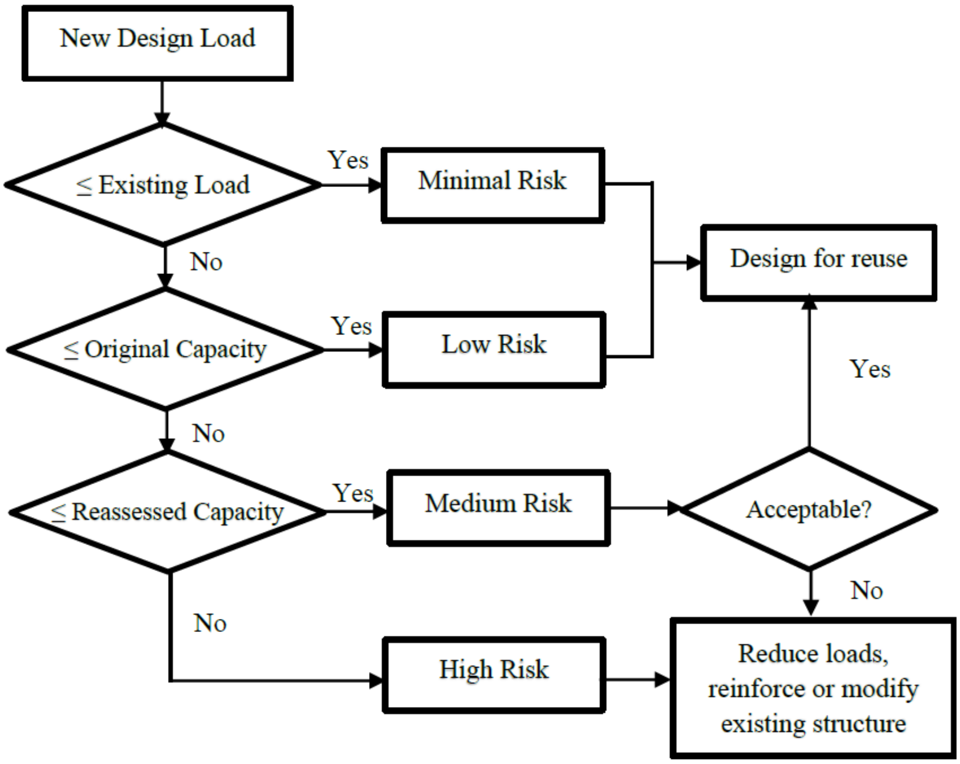

Figure 2.1: Assessment Process for New Design Loading.

2.2.4 Wind Load

Wind load is the lateral load exerted on the building due to the movement of air or wind. A wind moment will be formed at the foundation when a structure is subjected to wind load. As the moment is the product of force and its perpendicular distance from the reference point, an increase in height due to the additional storeys will undoubtedly increase the moment at the foundation of the building. According to Papageorgiou (2016), an increase in the moment is proportionally much greater than the increase in the height of the building. Hence, it is necessary to consider the increase in wind loading due to the additional storeys, especially in shorter buildings. This is to identify whether the increased moment could be taken up by the potential reserve bearing capacity of the foundation or new foundation is needed to avoid overturning. Consideration of the increase in wind loading also aids in the design of the wind force-resisting system.

2.3 Strategies for Vertical Extensions

Several completed case studies for the vertical extensions project were studied. The common techniques or methods adopted in the extension projects were identified. In many cases or researches, it was suggested that the adoption of lightweight structural elements could be an alternative to reduce the stress exerted on the existing structural system (Papageorgiou, 2016; Sundling, 2019; Soikkeli, 2016; E and Memari, 2014). Besides, modifications of the existing structural systems or the addition of a new framing system due to the extension will be described briefly in the following subsection.

2.3.1 Lightweight Extensions

The addition of storeys corresponds to an increase in weight of the existing building. Therefore, engineers often strive to design the extensions with the lightest possible structure. For example, the light-gauge steel frame and cross-laminated timber (CLT) frame. The selection of the type of frame to use depends on the characteristics of the structure to be built and may vary in every extension project. However, throughout the review of the existing applications and research, it was found that light-gauge steelwork is considered to be the most common material choice for an extension project.

Galvanised cold-formed steel (CFS) is the main structural component of the light-gauge steel systems. The light-gauge steel system is practical and appropriate for an extension due to its lower weight when compared to the traditional materials. Particularly, when compared to a similar concrete building, the light-gauge steel framing systems outperformed by a factor of five in terms of their weight, as their weight is only one-fifth of the concrete building (Burstrand, 2000). Hence, fewer resources will be needed to reinforce or strengthen the existing structure, thereby reducing the extension cost (Bergsten, 2005). Apart from that, other research and experiences have confirmed that applying the light-steel gauge system can bring numerous advantages. These include good structural performance, ease of construction and deconstruction, precision and consistent quality, thermal comfort, longevity, good sound insulation, high level of prefabrication and being environmentally friendly due to recycling and re-use of the material.

Another essential feature of extensions worth noting is their construction methods, i.e. modular construction methods. According to E and Memari (2014), modular construction is suitable for structures with repetitive floor plan elements and is well-suited for projects that would benefit significantly from off-site construction, less disruption to community or business operations, and construction schedule time savings. In that case, the wall, floor, and roof structures are constructed as prefabricated modular pieces in the factories. These prefabricated modular units will either form a module alone or a functional whole in combination with other units and then assemble at the site. Using prefabricated modules to raise or extend a building will shorten the time on the site, minimize the need to reinforce the existing structure, and reduce disturbance to the existing occupants and buildings and their surroundings. This is because the units are prefabricated to a great degree, and the installation of services which is a significant part of the building process, can be completed in weather-protected factory conditions.

2.3.2 Transfer Mechanisms

While designing the floor plan for the additional storeys, additional loads due to the extension must be transferred to the existing structure. Therefore, it is crucial to ensure that the additional loads will not be supported by the existing roof slab but rather by load-bearing walls, pillars or the beams below. Having that said, the location of the load-bearing structures below typically dictates the orientation and arrangement of the prefabricated units. However, problems may arise due to the location of load-bearing structures below the extension or the difference in the structural system of the extension and the existing structure. In that case, it is possible to install large transfer beams or trusses on top of the existing roof structure to act as a transitional substructure. The beams or trusses distribute and resolve the vertical and lateral load paths and transfer from the extension to the existing structure (E and Memari, 2014).

The installation of the beams or trusses will raise the extension, which must be considered while extending staircases and installing facades. Soikkeli (2016) points out that the steel beams are the most practical option because they prevent the new modules from getting too tall. Apart from that, when beams or trussed structures are utilised, it allows flexibility in the layout of the modular units and provides space for heating, ventilation conduits and plumbing. Furthermore, the beams can also provide a flat platform for the modular units to be installed; when compared to old roof slabs, which may be somewhat uneven (Soikkeli, 2016).

2.3.3 Structural Interventions

Structural remediation is needed to withstand the additional loads if the structural system or the element within the structural system does not have sufficient capacity. Schwinger claims that either the existing structural system can be reinforced or a new framing system can be introduced to bear the additional loads. Among the two options, strengthening existing structural elements is often more cost-effective and more manageable when compared to the latter. The available techniques for reinforcing the columns, beams, slabs, walls and foundations are summarized in Table 2.2.

Table 2.2: Structural Interventions Techniques for Different Structural Elements.

Structural Elements	**Techniques**	**Description**
RC columns	Fiber Reinforced Polymers (FRP)	• Encase the column with FRP sheets or prefabricated jacketing. • Increase the original design strength and axial load carrying capacity of the column
	Circularization and FRP confinement	• Convert a square column to a circular column using segmental circular concrete covers of various concrete strengths and encase with CFRP sheets. • Increase load-bearing capacity.
	Steel jacketing	• Reinforce columns with steel angles linked by horizontal strips to increase column capacity.
	Concrete jacket with additional reinforcement	• Enlarge column section with additional concrete that surrounds the column and be equipped with closed stirrups. • Increase column's stiffness and moment of inertia and lowering internal stresses.
RC beams	Concrete jacketing	• Enlarge cross-section by adding a new layer of concrete that is provided with longitudinal and transverse reinforcement
	Carbon Fibre Reinforced Polymer (CFRP)	• Wrap the RC beams with CFRP sheets • Increase the shear capacity of reinforced concrete beams

Table 2.2 (Continued)

Slabs	Fiber Reinforced Polymers (FRP)	• Encase the concrete members with FRP sheets to improve load-bearing capacity.
	Bonded steel elements	• Bond the steel elements to the concrete surface to form a composite structure • Improve flexural or shear strength
Foundation	Altering the properties of bed soils	• It can be done by grouting, thermal and electrochemical stabilisation, silicification
	Altering the foundation design	• It can be done by installing additional piles, monolithic yokes, micro piling and so on.
	Redistributing active forces	• It can be done by installing monolithic girdles, unloading frames, or force transmission to nearby components.
Walls	Concrete jacketing	• Use high-performance concrete with high strength steel mesh to increase ductility, deformation capacity and structural resistance. • Or use cement mortar reinforced with glass fibre reinforced plastics grids to increase lateral load-bearing capacity.
	Externally bonded steel strips	• Applied bonding steel strips externally on both sides of a wall in symmetrical configurations to improve strength and ductility
	Fiber Reinforced Polymers (FRP)	• Externally bonded FRP to the walls to increase shear or flexural strength, energy dissipation and stiffness.

As shown in Table 2.2, there are many methods to strengthen the existing structural elements. It is essential to evaluate the cost, and the structural engineer shall determine the possible risk for each intervention and the most suitable approach, which may vary from case to case.

2.3.4 Addition of New Framing Structure

As mentioned earlier, the addition of a new framing system is the alternative option to support the additional weight due to the extension. Remarkably, the extension can be independently supported by integrating an exoskeleton and new foundations. Aside from that, in some instances, the existing structural system is converted into a new structural system by adding new structural components or shear cores (Papageorgiou, 2016).

2.4 Carbon Impact

Generally, carbon footprint refers to the total quantity of greenhouse gases generated by operations or activities and is often quantified in tonnes of CO_2 equivalent (tCO_2e). CO_2 emissions are closely related to climate change and global warming that bring adverse implications to humans and the environment. The greenhouse gases tend to trap heat in the atmosphere, resulting in increased global temperature. According to the statistics, the construction industry is a major contributor of carbon dioxide (CO_2) to the ambient air (Ali, Ahmad and Yusup, 2020). The processes of construction of buildings, operations, maintenance and service, and the embodied carbon of the materials used to construct the structure have resulted in a tremendous amount of CO_2 being released into the atmosphere. As a result, the carbon impact of a building must always be considered to ensure that the design of the building achieves the least amount of negative environmental consequences.

2.5 Summary

A detailed discussion of the technical challenges and typical design considerations associated with vertical extension were included in this chapter. The common trends observed in available research and completed projects were described in detail. The main parameters and possibilities of the structural solutions for the vertical extension as the literature review outcomes will be verified thereafter through the simulation with SCIA engineer software. After performing the literature review, it was discovered that the vertical extension's environmental impact or carbon emission was not well-explained in all the cases. Besides, none of the present studies compares the environmental impact of vertical extension with demolition and reconstruction. Therefore, the ultimate goal of this project is to examine the possibility of vertical extension and its sustainability level compared to demolition and reconstruction.

CHAPTER 3

METHODOLOGY AND WORK PLAN

3.1 Introduction

This chapter focuses on the comprehensive methodology and work plan to meet the aim and objectives of this project. The detailed processes involved in the execution of the research are discussed and explained. The project flowchart is shown in the first section of this chapter. Next, the structural analysis software used in this research is introduced, and the processes to carry out the simulation using SCIA Engineer are discussed. The modelling and analysis processes begin with the existing building model, followed by the extended building model. The dimensions of the structural elements, material properties, and the actions acting on the building models are covered in this chapter. Subsequently, the methodology for computing carbon impact resulting from the vertical extension is discussed. Lastly, the summary is presented at the end of this chapter.

3.2 Research Flowchart

This research started with modelling of the existing building with SCIA Engineer software. Next, linear analysis was performed on the existing building model to study its structural performance. Then, the concept of the extension was developed by determining the location and height of the expansion. The extension modules were designed and assigned with appropriate materials with the aid of Revit software. Besides, preliminary load assessments were performed accordingly to determine the extra loadings incurred due to the expansion. Afterwards, the existing model was extended vertically with two additional storeys with the structural analysis software, and the structural performance of the extended building model was evaluated. Subsequently, the carbon footprint due to the extension as well as demolition and reconstruction were evaluated with Revit and IStructE guide. Finally, the relevant results were presented and discussed. The complete workflow for this research is illustrated in Figure 3.1.

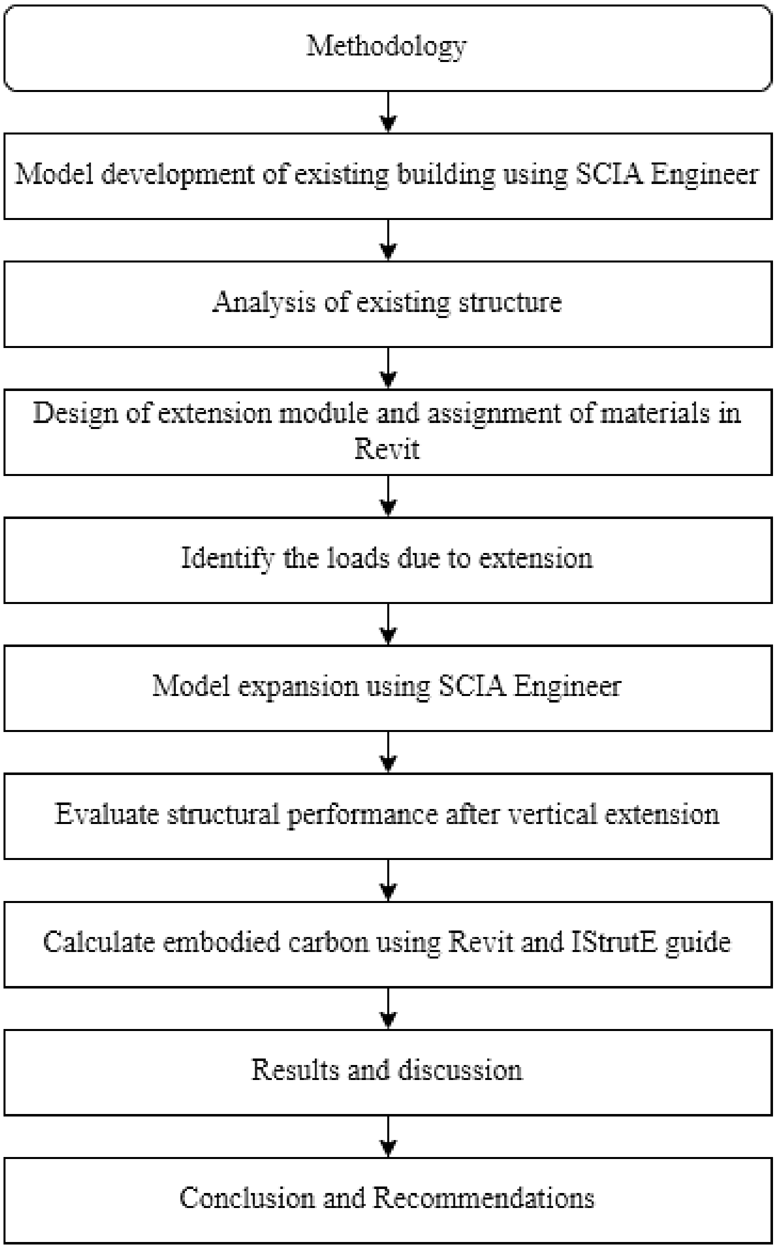

Figure 3.1: Flowchart of Methodology.

3.3 Design Codes and Standards

The design of both the existing building and extension are in accordance with the Eurocode. The referencing design codes and standards are as follows:

1. MS-EN 1990: Basis of structural design
2. MS-EN 1991-1-4: General actions – Wind actions
3. MS-EN 1992-1-1: General rules and rules for buildings
4. MS-EN 1992-1-2: General rules – Structural fire design
5. MS-EN 1993: Design of steel structures
6. MS-EN 1994: Design of composite steel and concrete structures

3.4 Structural Modelling and Analysis Using SCIA Engineer

The renowned software SCIA Engineer was used to analyse and model the structural system in this study. SCIA Engineer software is a Building Information Modelling (BIM) software that can be utilised for rapid and precise modelling, analysis and optimisation of a 3D model of any structure, loading conditions or materials (SCIA, 2021). Besides, SCIA provides complete coverage of the design code – Eurocode, National Annexes and other international standards. Every procedure is handled carefully to ensure that all limitations and factors affecting the structural system are considered. Since the original design details of the existing structure were not available, the design of the existing structure was carried out using SCIA Engineer software to determine the structural system of the existing building. Figure 3.2 depicts the general procedures in modelling and analysing the structural system using SCIA Engineer software.

Prior to the modelling process, the basic data of the project including the material data were defined in the software. The Eurocode, Malaysia National Annex were utilised as reference codes for all material properties, loading assignments and design. Then, the proposed cross-sections were defined in the software. Subsequently, the structural framing was modelled using the defined sections, and the boundary conditions were defined. Afterwards, the load cases and load combinations were generated before assigning the loadings to the building model. The load cases included in this study are permanent, imposed and wind loads. Next, linear analysis was performed, and the critical structural elements were identified. In the event that failure checking of the structural members is not passed, a new section is proposed and reanalysed the building until all checking is passed. The modelling of the existing building and the vertical extension will follow the same methods. The vertically extended building model analysis is essential; failure in the analysis of the extended building model indicates that redesigning and retrofitting of the existing structural elements is required.

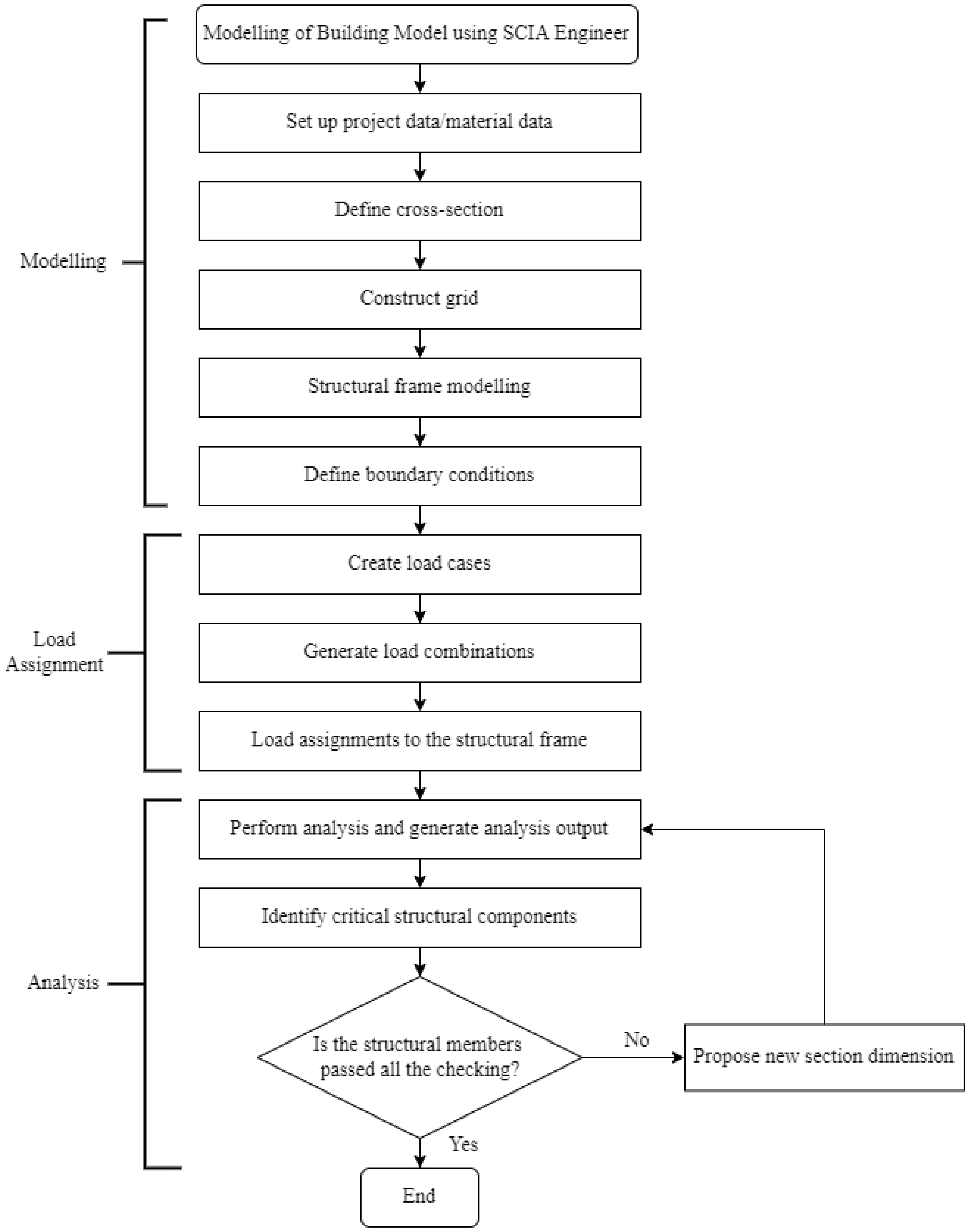

Figure 3.2: General Procedures for Structural Modelling and Structural Analysis in SCIA Engineer Software.

3.5 Modelling of Existing Structure

The target existing building is a G + 11 multi-storeys residential building with a two-storey basement car park. Since the original design details of the existing structure were not readily available, the design for the existing structure was performed using SCIA Engineer to determine its structural system. The general information and characteristics of the existing structural set under the Eurocode are as follows:

General Information

Type of construction	RC framed	
Type of walls	Brick wall	
Boundary condition	Fixed	

Floor Height

Total height from ground	45.5m	
Basement 2	3.525 m	
Basement 1	4.075 m	
Ground floor	4.8 m	
All other floors	3.7 m	

Eurocode

Reliability class	RC2	
Design service life class	3	50 years
Functional class	A	Residential building
Fire safety	90 min	

Material properties

In-situ concrete	C30/37	Existing structure
Steel	B 500B	Reinforcement of existing structure

The referenced standards for the design of the existing building are in line with the current codes of practice. Before the modelling process, the properties of concrete and steel reinforcement were defined in the software. The detailed properties were summarised in Table 3.1 and Table 3.2, respectively.

Table 3.1: Concrete Properties.

Properties	Unit
Unit mass	2500 kg/m^3
Elastic Modulus, E	3.280 E+04 MPa
Shear Modulus, G	1.3667 E+04 MPa
Characteristic Compressive Strength, f_{ck}	30 MPa

Table 3.2: Steel Reinforcement Properties.

Properties	**Unit**
Unit Mass	7850 kg/m^3
Elastic Modulus, E	2.000 E+05 MPa
Shear Modulus, G	8.3333 E+04 MPa
Characteristic Yield Strength, f_{yk}	500 MPa
Maximum tensile strength, f_{tk}	540 MPa

Modelling the existing building involves constructing structural components such as beams, slabs, columns, and walls. The structural elements of the existing building model were located based on the C&S drawings and building layout plan. The layout plan for the existing building model is shown in Figure 3.3, and the structural system of the existing building is illustrated in Figure 3.4.

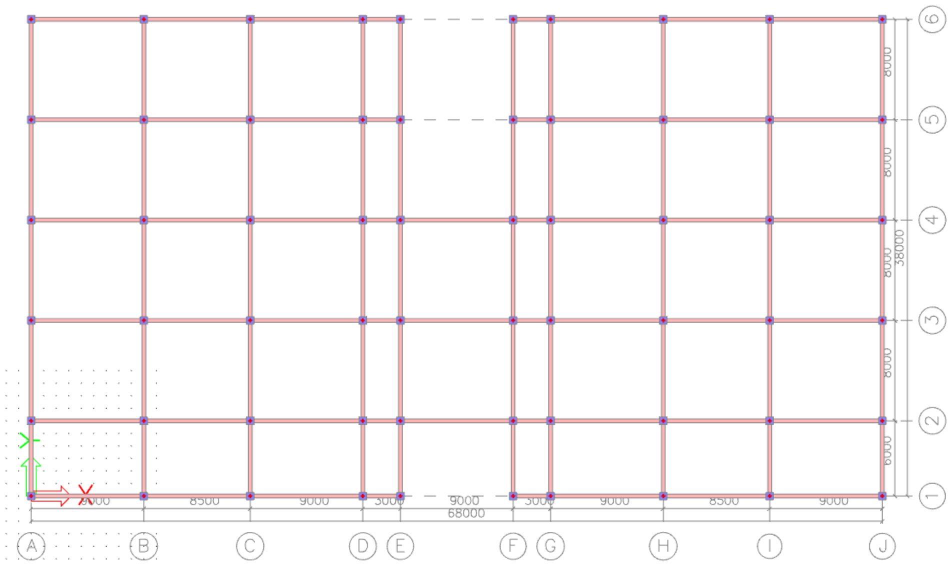

Figure 3.3: Layout for the Residential Floor of Existing Building Model.

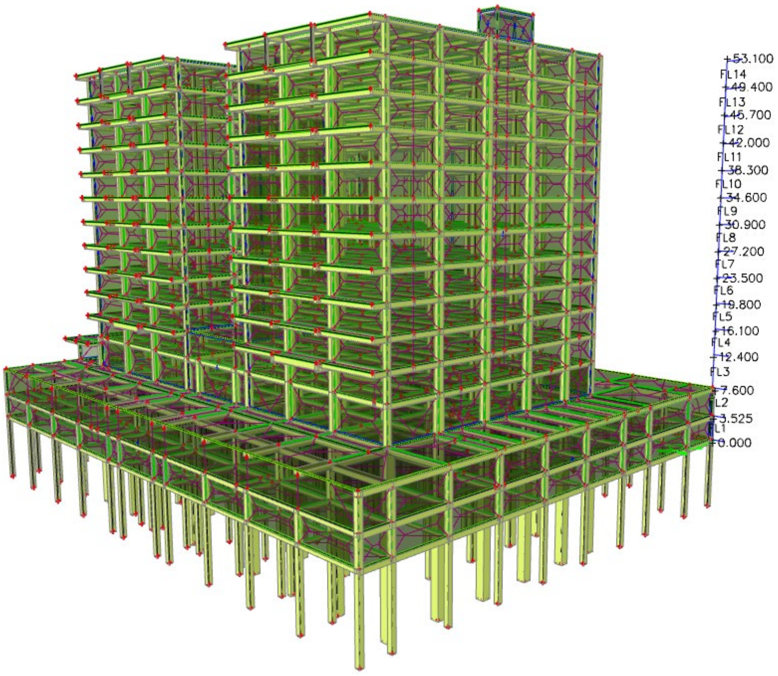

Figure 3.4: Structural System of the Existing Building Model.

As shown in Figure 3.3, a rectangular line grid was generated as a guideline to plot the nodes and locate the structural members. The columns were assigned to the corners of the building and at every intersection. In this study, columns were the only vertical components used in structural modelling. Beams were connected to the vertical members and were included on every floor. The slabs of the model on every floor, including the roof slab, were represented by the load panels. The existing building was designed with a flat roof, making it suitable for the vertical extension. Besides, load panels were assigned to the outer surface of the building model, representing the wall where the wind load is acting on it. The dimensions of each structural element used for the existing building model were tabulated in Table 3.3. Apart from that, the end condition of the foundation was set to be fixed as the foundation is a pile cap with piles, and the columns are fixed within it.

Table 3.3: Dimensions of Structural Components for the Existing Building.

Structural Components	Description
Dimension of outside column (b × h)	1200 mm × 600 mm
Dimension of inside column (b × h)	900 mm × 600 mm
Dimension of primary beam (b × h)	300 mm × 600 mm
Dimension of secondary beam (b × h)	225 mm × 450 mm
Thickness of slab (basement)	500 mm
Thickness of slab (other floors)	150 mm
Thickness of wall	100 mm

3.6 Actions on Existing Structure

The first step in analysing the existing structure is the identification of the loadings applied to the different structural parts. The load cases to be considered include permanent, imposed, and wind loads. The information for all the loadings acting on the existing structure was discussed in the following sub-sections.

3.6.1 Permanent Load

The permanent loads acting on the structure resulted from the self-weight of the structure, brick wall, floor finishes, ceiling and services. With the defined material properties and section dimensions, the self-weight of the beams and columns can be generated in the software. SCIA Engineer software is able to compute and assign the self-weight of all members easily using "Self-weight" force with a gravity coefficient of "-1" to represent downward force. Other permanent loads were derived from unit weights. Additionally, the permanent load acting on the slab due to ceiling and services was assumed to be 0.50 kN/m^2. Table 3.4 summarises the main permanent loads acting on the concrete slab. The brick wall transferred its loading as a line load to the beam. The permanent load of brick walls exerting on beams for different floor levels was tabulated in Table 3.5. The line load was obtained by multiplying the weight per unit area of a 100 mm brick wall with the corresponding height for each floor. A value of 2.6 kN/m^2 was assumed for the standard weight per unit area of a 100 mm brick wall.

Table 3.4: Permanent Actions on the Existing Structure.

	Thickness (mm)	Loads, g_k (kN/m^2)
Basement		
Concrete slab	500	12.5
Floor finishes	50	1.00
Ceiling and services	-	0.50
Total		14.00
Other floors		
Concrete slab	150	3.30
Floor finishes	50	1.00
Ceiling and services	-	0.50
Total		4.80

Table 3.5: Permanent Loads due to Brick Wall.

Floor	Brick wall load (kN/m^2)	Height (m)	Line load (kN/m)
Basement 2	2.6	3.525	9.165
Basement 1	2.6	4.075	10.595
Ground floor	2.6	4.8	12.48
All other floors	2.6	3.7	9.62

3.6.2 Imposed Load

The imposed load, also known as live load, is a variable load in which distinct categories and specific usage of the loaded region may have different uniform distributed loads, q_k. Table 3.6 presents the imposed loads for the existing structure with respect to the categories and specific uses. The categorisation of the imposed loads and the suggested imposed loads were in accordance with MS EN 1991-1-1:2010. In this study, imposed loads for the traffic area were considered for the basement car park (B2 – B1) and exterior area of the ground floor. Other floor areas were assigned with the value under the domestic and residential area category.

Table 3.6: Imposed Loads on Different Loaded Areas (Department of Standards Malaysia, 2010)

Specific Use	**Category**	**Imposed Loads, q_k (kN/m^2)**
Areas for domestic and residential activities	A	2.0
Traffic and parking areas for light vehicles (gross vehicle weight ≤ 30 kN)	F	2.5

3.6.3 Wind Load

In this research, wind loads acting on structures were simulated using the 3D Wind-Load Generator in accordance with the European Standard. According to SCIA Engineer Software (2022), 3D Wind-Load Generator is a complex and excellent tool that allows for a more straightforward assessment and illustration of wind pressure coefficient and wind loads assigned to various locations. Before the wind loads can be created, the 2D members that form the structural model's exterior surface were set with the property 3D wind so that the wind load generator will consider the selected 2D member. Wind load cases with different wind directions (0º, 90º, 180º and 270º) and "plus" and "minus" combination of external pressure (Cpe) and internal pressure (Cpi) coefficients were covered for this research. Table 3.7 summarises the wind load cases generated in software.

Table 3.7: Wind Load Cases.

Direction	**+ CPE, + CPI**	**+ CPE, – CPI**	**– CPE, + CPI**	**– CPE, – CPI**	**+ CPI**	**– CPI**
0	✓	✓	✓	✓	0.20	– 0.30
90	✓	✓	✓	✓	0.20	– 0.30
180	✓	✓	✓	✓	0.20	– 0.30
270	✓	✓	✓	✓	0.20	– 0.30

3.6.4 Load Combinations

In order to assure the safety of the structure under a variety of maximum loading conditions, the load combinations were considered to identify the ultimate state of the building. The combination of actions for permanent and transient situations was adopted in compliance with MS EN 1990-2002 cl. 6.4.3.2(3). The ultimate design load for this study was obtained using Equation (3.2.

$$1.3\ G_k + 1.5\ Q_{k,1} + 0.75\ Q_{k,w} \tag{3.1}$$

where:

G_k = permanent load

$Q_{k,1}$ = live load

$Q_{k,w}$ = wind load

3.7 Strategies for Implementation

The residential building (with two storeys basement car park) of G + 11 stories is vertically expanded to G + 13 by introducing additional two floors. Two scenarios were covered in this research to compare the carbon impact of vertical extension with demolition and reconstruction of the structure. The conditions for each scenario are summarised in Table 3.8.

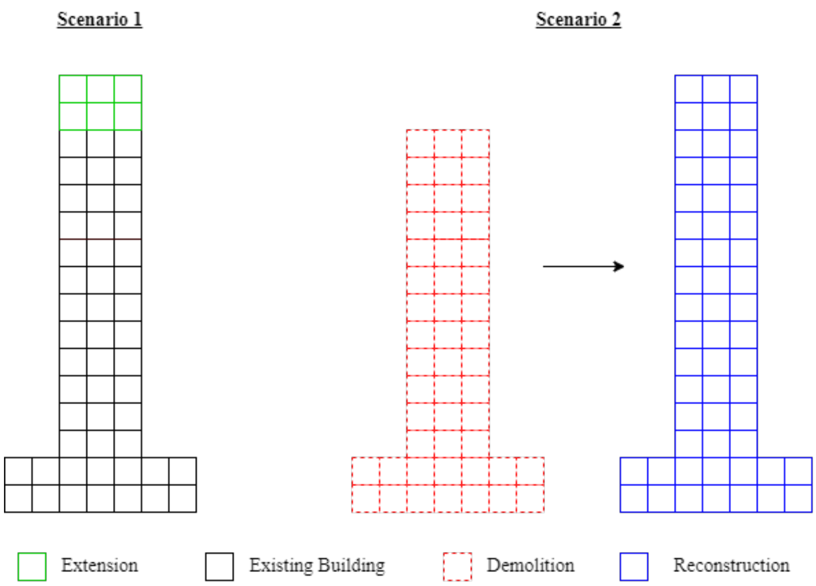

Figure 3.5: Schematic Representation of the Design Scenarios.

Table 3.8: Description of the Design Scenarios.

Scenarios	Description
Scenario 1	Vertical extension of two storeys with light-gauge steelwork
Scenario 2	Demolition and new construction of the building

3.8 Model Expansion

As mentioned previously, SCIA Engineer was adopted to analyse the extended building model to identify the need for redesigning and retrofitting measures. Figure 3.6 shows the 3D rendering view of the vertically expanded building model. Figure 3.7 depicts the layout plan for the location and placement of the extension modules on the existing building model.

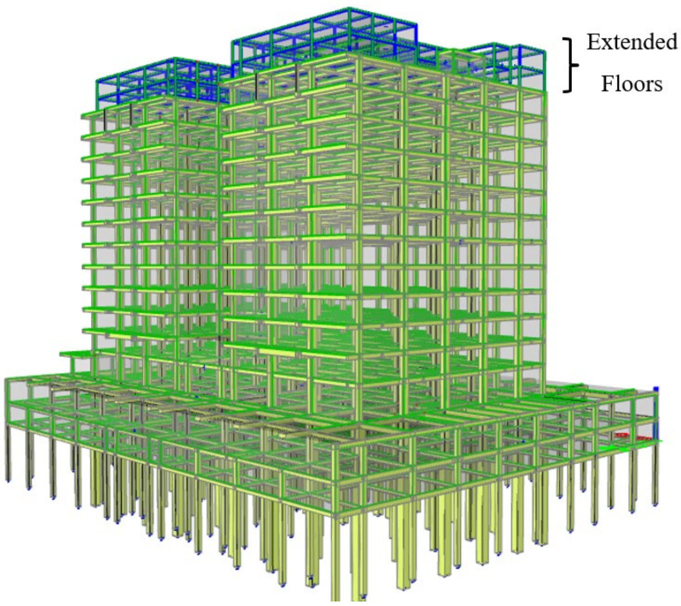

Figure 3.6: Vertical Extension on Existing Building Model.

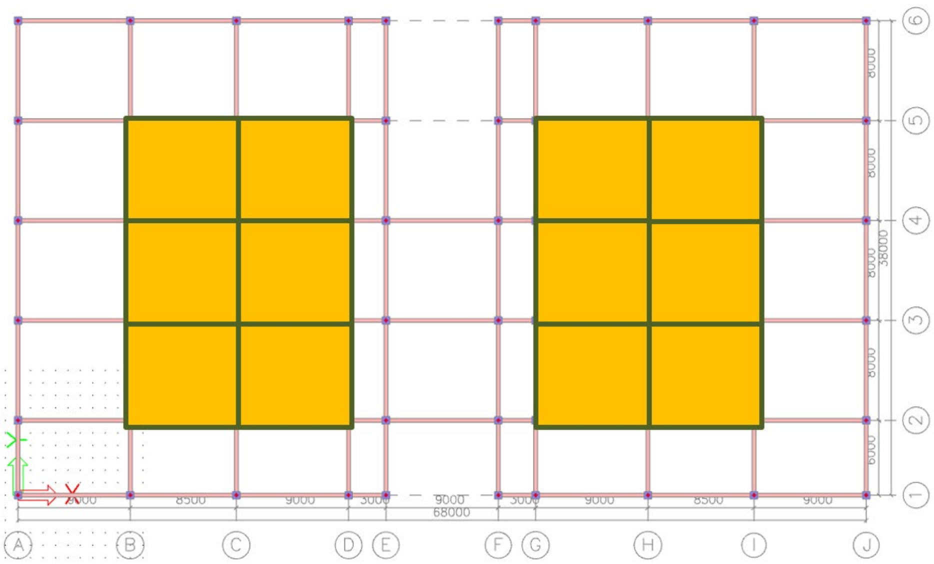

Figure 3.7: Location and Placement of Extension Modules.

3.8.1 Design of New Block

In this study, modular construction was adopted to add new floors. The selection of module type depends on the architectural and structural performance. The module selection is pivotal as it contributes to loads of the extension added on top of the existing roof slab. Light-gauge steelwork was used as the primary structural material in this research. The advantages of modular construction and light-gauge steelwork have been emphasised in the literature review. The height of the extension module is 3.0 m. Identifying construction types and materials used is essential for preliminary load assessments. Table 3.9 shows the structural components used for the extension units. Table 3.10 and Table 3.11 summarise the material properties of the precast concrete block with grade 40/50 and light-gauge steel, respectively.

Table 3.9: Structural Components of Extension Units.

Structural Components	Description
Dimension of column	SHS 120 × 120 × 6.0
Dimension of beam	RHS 250 × 100 × 6.3
Thickness of slab	150 mm
Thickness of brick wall	100 mm

Table 3.10: Precast Concrete Block (40/50) Properties.

Properties	Unit
Unit mass	2200 kg/m^3
Elastic Modulus, *E*	2.991 E+04 MPa
Shear Modulus, *G*	1.2463 E+04 MPa
Characteristic Compressive Strength, f_{ck}	35 MPa

Table 3.11: Material Properties for Structural Steelwork.

Properties	Unit
Unit Mass	7850 kg/m^3
Elastic Modulus, *E*	2.100 E+05 MPa
Shear Modulus, *G*	8.0769 E+04 MPa
Ultimate Strength	490 MPa
Yield Strength	355 MPa

The extension module was designed and modelled using Revit software. Figure 3.8 illustrates the typical extension module that was constructed with Revit. The structural materials for the extension module were assigned accordingly in Revit software.

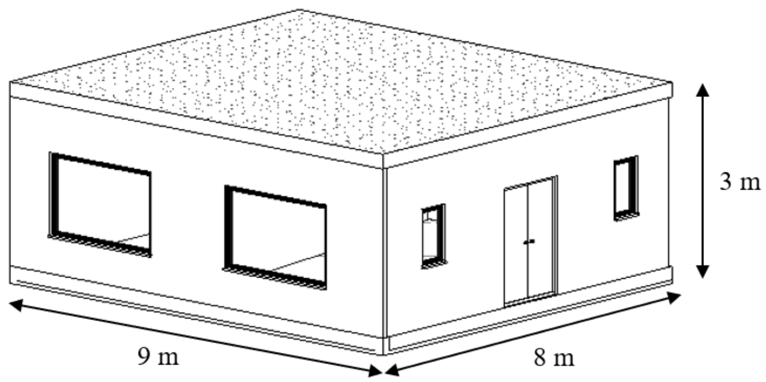

Figure 3.8: 3D View of an Extension Module.

Then, a loading analysis was carried out to identify the additional loadings due to the extension and its impact on the existing structural system. The permanent loads were derived using the same method as in the loading analysis of the existing building model. Table 3.12 summarises the permanent actions for the extension unit. As the function of the extension unit is the same as the existing building, i.e. residential, the imposed load was categorised under category A, and the imposed load was taken as 2.0 kN/m^2, as presented in Table 3.6.

Table 3.12: Permanent Actions on Extension Units.

	Thickness (mm)	g_k **(kN/m)**	g_k **(kN/m^2)**
Concrete slab	150	-	3.75
Floor finishes	50	-	1.00
Ceiling and services	-	-	0.50
Brick wall (3 m height)	100	5.76	
Total		5.76	5.25

3.9 Analysis of Results

After constructing structural framing and loading assignments, a linear analysis was performed on the existing and extended building models. The analysis outputs were generated and compared for both models. In order to make the analysis and investigation process more efficient, the emphasis was paid to the structural elements that will be most impacted by the increased gravity and lateral stresses during vertical extension. The primary structural components that contribute to the smooth passage of gravity and lateral loads to the foundation include the floor slabs, columns, stability walls and the shear core. Since introducing additional floors on top of an existing building does not affect the concrete floor slabs, they were omitted from the critical components. Furthermore, this study did not cover the stability walls and shear core. Hence, the focus on the critical structural element was paid to the columns only. The results of support reactions were considered in the comparative analysis.

3.10 Demolition and Reconstruction

The main goal of studying demolition and reconstruction is to compare the resulting carbon emissions with vertical extension. The existing building and the proposed new construction were modelled in Revit to obtain the quantities of each structural material for the computation of embodied carbon. Figure 3.9 illustrates the building model of the proposed new construction; G + 13 stories with two storeys basement car park. The materials and structural elements used for the new structure were similar to that of the existing building model, as presented in Section 3.5. The bill of material and procedures for computing embodied carbon were discussed in the following sub-sections.

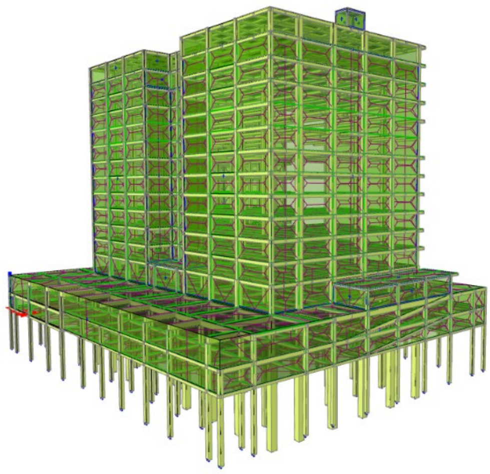

Figure 3.9: Modelling of Building for New Construction in SCIA.

3.11 Carbon Impact

The environmental assessment was performed to estimate the environmental implications of the project. The evaluation can be carried out for vertical extension by following the calculation guidelines. Life cycle analysis (LCA) is a technique for assessing the environmental effect of a given product or service from the material manufacturing stage to the end-of-life stage. Table 3.13 presents the life cycle stages for the environmental evaluation of the building construction based on BS EN 15798:2011. The building life cycle is broken down into the production and construction stage (Module A), followed by the use stage (Module B), and finally, the disposal stage (Module C). In this research, the embodied carbon of vertical building extension was evaluated according to different lifecycle modules throughout the building's life cycle.

Table 3.13: Life Cycle Stages and Modules for Building Assessment.

BUILDING ASSESSMENT INFORMATION																
BUILDING LIFE CYCLE INFORMATION																**Beyond building life cycle**
Product stage			**Construction process stage**		**Use Stage**							**End of life stage**				
A1	**A2**	**A3**	**A4**	**A5**	**B1**	**B2**	**B3**	**B4**	**B5**	**B6**	**B7**	**C1**	**C2**	**C3**	**C4**	**D**
Raw material supply	Transport	Manufacturing	Transport	Construction Installation process	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	De-construction demolition	Transport	Waste process	Disposal	Benefits and loads
																Reuse-Recovery-Recycling-potential

3.11.1 Estimation of Embodied Carbon Using Revit

Hawkins\Brown Emissions Reduction Tool (H\B:ERT) is a simple carbon measuring tool that integrates with Revit that allows the designers to analyse embodied carbon emissions of various building elements and construction materials during the design process. The volume and weight of all materials assigned in the Revit model were measured by H\B:ERT. The information on the structural materials for the extension module, existing building and new construction was tabulated in Table 3.14, Table 3.15 and Table 3.16, respectively. Then, the tool integrates the embodied carbon data to the specified material, divided into life cycle phases in compliance with BS EN 15978:2011, as presented in Table 3.13. The embodied carbon data for the relevant structural materials covered in this research were summarised in Table 3.17. With the embodied carbon data specified, H\B:ERT will automatically generate the embodied carbon (EC) for respective structural materials. It is worth noting that the total carbon emissions for the extension module and reconstruction will generally cover all modules for a building life cycle. To be specific, the EC for material production, transportation, construction and replacement are covered. In contrast, demolition of structure was categorised under the end-of-life stage, whereby only overall end of life EC was being considered.

Table 3.14: Structural Materials Information for an Extension Module.

Material	**Volume (m^3)**	**Density (ton/m^3)**	**Weight (ton)**
Brick	151.20	1.920	290.153
Cold Formed Steel	2.88	7.800	22.464
Concrete - Precast Block 40/50	536.16	2.200	1179.592
Gypsum Plasterboard	91.44	0.800	73.246

Table 3.15: Structural Materials Information for Existing Building.

Material	Volume (m^3)	Density (ton/m^3)	Weight (ton)
Brick	1475.29	1.920	2832.557
Concrete in situ – RC 30/37	12821.33	2.500	32053.325
Gypsum Plasterboard	1779.07	0.800	1423.256

Table 3.16: Structural Materials Information New Construction.

Material	Volume (m^3)	Density (ton/m^3)	Weight (ton)
Brick	1683.31	1.920	3231.955
Concrete in situ – RC 30/37	21769.86	2.500	54424.650
Gypsum Plasterboard	2075.59	0.800	1660.472

Table 3.17: Embodied Carbon Data for Typical Structural Materials in H\B:ERT Library.

Material	Waste rate (%)	Material EC ($tonCO_2/ton$)	Transport coefficient (%)	Construction coefficient (%)	Replacements over 60 years	End of life coefficient (%)
Brick	0.200	0.210	0.03	0.07	0	0.02
Cold Formed Steel	0.150	2.730	0.03	0.07	0	0.02
Concrete in situ – RC 30/37	0.050	0.129	0.03	0.07	0	0.02
Concrete - Precast Block 40/50	0.010	0.148	0.03	0.07	0	0.02
Gypsum Plasterboard	0.225	0.390	0.03	0.07	1	0.02

3.11.2 Estimation of Embodied Carbon Using IStructE Guide

According to the IStuctE guide, the embodied carbon of the structures can be determined using Equation (3.2:

$$EC\ (tCO_2e) = \text{quantity (ton)} \times \text{carbon factor} \tag{3.2}$$

The quantity here refers to the quantity of each material. The quantities of the materials obtained from Revit, as presented in Table 3.14, were used in this case. On the other hand, the carbon factors (in $kgCO_2e$ per kg of material) were split into different lifecycle modules. The calculation of embodied carbon for IStructE covers only the production and construction stage of the structural material since they are likely to contribute to the majority of the embodied carbon of the designs. Table 3.18 summarises the embodied carbon factor (ECF) for the structural materials used in the extension module. The carbon factors for various structural materials at production (A1 – A3) and transport (A4) stages can be referred to Appendix A. All the materials were assumed to be locally manufactured.

Table 3.18: Embodied Carbon Factors (ECF) for Typical Structural Materials Based on IStructE Guide.

		ECF ($kg/CO_2e/kg$)		
Material	**Waste Factor**	**A1-A3 (Production)**	**A4 (Transport)**	**A5w (Waste)**
Brick	0.250	0.213	0.005	0.059
Cold Formed Steel	0.010	1.550	0.005	0.016
Concrete in situ C30/37	0.053	0.103	0.005	0.007
Concrete - Precast Block 40/50	0.010	0.178	0.005	0.002
Gypsum Plasterboard	0.290	0.390	0.005	0.120
Steel Reinforcement	0.053	1.99	0.005	0.107

Unlike the A1 – A3 and A4 modules, there is no direct way to obtain the ECF for the material wastage stage. The ECF for the A5w stage was obtained by using Equation (3.3:

$$ECF_{A5w} = WF \times (A1 - A3 + A4 + C2 + C3 - C4) \quad (3.3)$$

where:

ECF_{A5w} = embodied carbon factor for module A5w

WF = waste factor (Table A-3 in Appendix A)

A1 – A3 = production of the wasted material, kg/CO_2e/kg (Table 3.18)

A4 = transportation of the wasted material to site, kg/CO_2e/kg (Table 3.18)

C2 = transportation of the wasted material away from site

= 0.005 kg/CO_2e/kg (assume 50 km by road to the nearest location)

C3 – C4 = ECF for processing and disposal of the waste material (1.77 kg/CO_2e/kg for timber products and 0.013 kg/CO_2e/kg for all other materials)

In addition, as specified in the IStructE guide, the carbon emissions for demolition and deconstruction of the structure shall encompass all site-based operations necessary to dismantle, deconstruct and demolish the constructed property. Owing to the absence of more specific information for the abovementioned activities, an average rate of 3.4 kgCO_2e/m^2 GIA recommended by the guide was adopted for carbon emissions during demolition in this study.

3.11.3 Structural Carbon Rating Scheme

Figure 3.10 depicts the Structural Carbon Rating Scheme (SCORS).

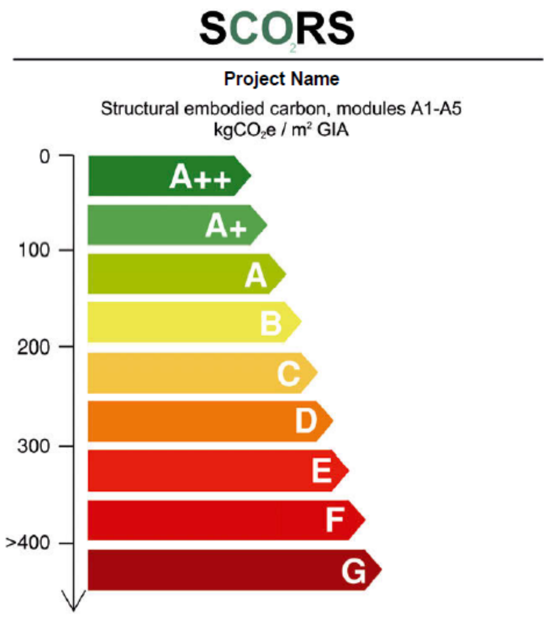

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Figure 3.10: Structural Carbon Rating Scheme (Arnold et al., 2020).

The structural embodied carbon of the two scenarios was compared using SCORS. The advantage of adopting SCORS is that it contextualises the carbon impact of a design and aids the designer in determining whether the design has a high or low embodied carbon footprint when compared to industry standards. It is worth noting that this rating system covers only the estimated A1 – A5 emissions. To utilise this rating system, the carbon footprint of modules A1 – A5 is divided by the gross internal area (GIA) of the extension module. The GIA of the extension module, existing building and new construction are 72 m^2, 40068.32 m^2 and 44840.32 m^2, respectively.

3.12 Summary

The analysis of the existing building was first performed. Subsequently, the proposed extension structures were added on top of the existing structure, and the effect of the added extension was evaluated. Another scenario covered in this study is the demolition and reconstruction of the building. The structural embodied carbon for both cases is estimated using Revit and IStructE guide, and the ratings were determined with reference to SCORS.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

This chapter presents the linear analysis results of the existing and extended building model obtained from SCIA Engineer. The support reactions of columns under ultimate limit state (ULS) and due to wind load in the critical direction identified and compared. In this chapter, the technical challenges associated with vertical extensions are discussed in depth. The carbon impact of the two proposed scenarios – vertical extension and demolition & reconstruction are evaluated and discussed in the last section of this chapter.

4.1 Results

In this research, load combinations under the ULS were studied for the estimation and analysis of the columns' support reactions. On top of that, a total of four load combinations were examined for both the existing and extended building model, with a wind flow direction of 270º and various "plus" and "minus" combinations of external pressure (CPE) and internal pressure (CPI), as summarised in Table 4.1. Through the analysis, it is worth noting that the structural components fulfil the ULS criteria and were able to sustain the additional load from two extended storeys. The structure was anticipated to be capable of handling the extra loads without strengthening of the structural elements.

Table 4.1: Load Combinations with 270º Wind Direction.

Load Combinations	Combinations of CPE and CPI
ULS1	3DWind - 270º, + CPE, + CPI
ULS2	3DWind - 270º, + CPE, - CPI
ULS3	3DWind - 270º, - CPE, + CPI
ULS4	3DWind - 270º, - CPE, - CPI

The evaluation of support reactions focuses on the wind flow direction of 270º despite the fact that different wind directions, namely 0º, 90º 180º and 270º were applied in the analysis. This is simply because a higher value of support reactions was acquired for 270º wind direction, representing the critical and most unfavourable condition of the building response among other wind directions. This can be explained, as for wind flow direction of 270º, the wind travels along the shorter width of the building models, as illustrated in Figure 4.1, thus creating a considerable wind load impact.

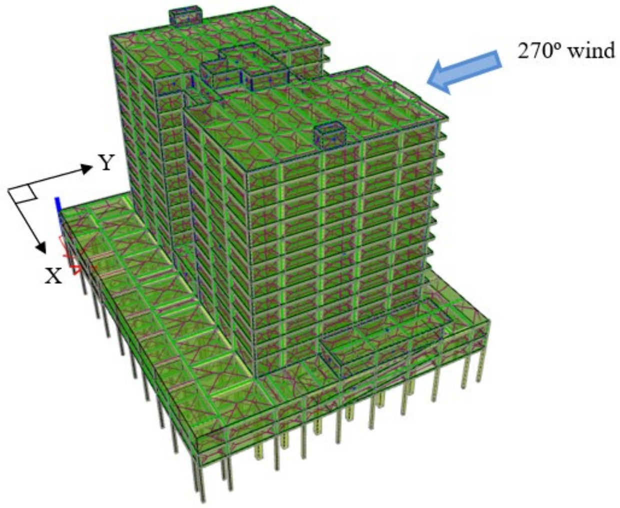


Figure 4.1: 270º Wind Direction to the Building Model.

4.1.1 Support Reactions for Existing Building Model Under ULS

Table 4.2 presents the result of the support reactions of the column under different load combinations. The most critical column was found at N2609, as illustrated in Figure 4.2, with the highest reaction force of 15611.1 kN under ULS1. Moreover, it is remarkable that the support reactions of the critical columns under ULS1 and ULS3 are approximately the same. The same scenario was observed for ULS2 and ULS4. It can be deduced that when the CPI have the same sign, the support reactions of the building owing to wind load impact tend to have equal values. Besides, there are only minor differences between the reaction forces of four types of load combinations. The minor discrepancies are possibly due to the slight difference in the wind loading.

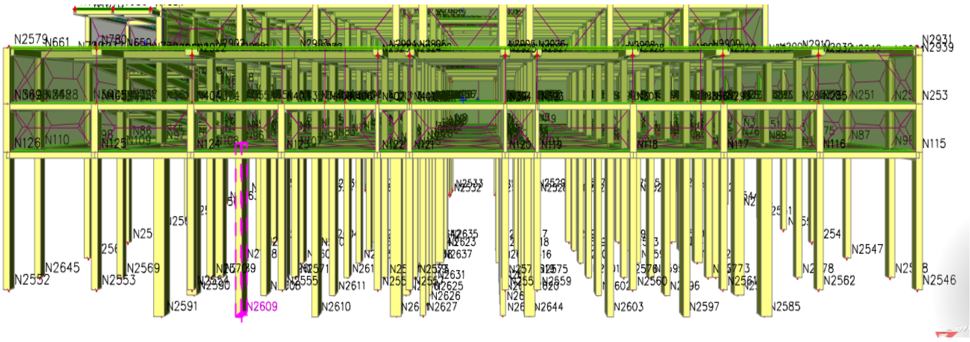


Figure 4.2: Nodes Labelling of the Building Model.

Table 4.2: Support Reactions for Existing Building Model Under Different Load Combinations.

Structure	Node	Reaction force, Rz (kN)			
		ULS1	ULS2	ULS3	ULS4
COL	Sn106/N2629	377.59	377.58	377.61	377.59
COL	Sn109/N2632	5682.89	5526.55	5676.07	5519.73
COL	Sn110/N2633	10745.27	10206.16	10743.86	10204.75
COL	Sn111/N2634	8548.78	8004.03	8544.68	7999.93
COL	Sn112/N2635	2337.62	2666.79	2337.61	2666.79
COL	Sn113/N2636	3372.04	3239.63	3370.93	3238.52
COL	Sn114/N2637	8605.55	9185.98	8606.43	9186.87
COL	Sn118/N2641	11498.10	11311.03	11497.57	11310.50
COL	Sn60/N2580	8403.62	9133.67	8397.10	9127.15
COL	Sn61/N2581	9736.92	9794.94	9727.52	9785.54
COL	Sn64/N2584	10705.57	10874.75	10705.88	10875.07
COL	Sn65/N2585	10194.60	10078.72	10195.25	10079.37
COL	Sn66/N2586	8946.81	9048.59	8939.84	9041.63
COL	Sn71/N2591	10750.86	10362.68	10728.25	10340.06
COL	Sn72/N2592	9897.83	10304.36	9879.38	10285.92
COL	Sn83/N2603	14608.81	14299.03	14608.53	14298.76
COL	Sn87/N2607	15209.48	15238.27	15208.86	15236.99
COL	Sn89/N2609	**15611.11**	**15268.42**	**15609.83**	**15267.80**
COL	Sn90/N2610	14966.18	14803.87	14965.83	14803.52

4.1.1 Support Reactions for Extended Building Model Under ULS

Table 4.3 displays the support reactions of columns of the extended building model under different ULS combinations. The column with the highest reaction force was found at N2609, with a maximum value of 15699.72 kN under ULS1. A similar trend is expected for the extended building. The reaction forces under ULS1 and ULS3 are close to each other, and that the identical scenario has been demonstrated in ULS2 and ULS4.

Table 4.3: Support Reactions for Extended Building Model Under Different Load Combinations.

Structure	**Node**	**Reaction force, Rz (kN)**			
		ULS1	**ULS2**	**ULS3**	**ULS4**
COL	Sn106/N2629	378.49	378.49	378.50	378.50
COL	Sn109/N2632	5791.20	5579.27	5783.66	5556.01
COL	Sn110/N2633	11121.41	10425.20	11118.33	10430.23
COL	Sn111/N2634	8900.92	8221.10	8892.10	8269.27
COL	Sn112/N2635	2426.09	2829.24	2425.38	2813.22
COL	Sn113/N2636	3525.87	3368.08	3524.02	3398.04
COL	Sn114/N2637	8788.12	10014.64	8787.34	10265.60
COL	Sn118/N2641	11523.08	12209.23	11522.39	12335.10
COL	Sn60/N2580	8587.41	9354.26	8573.41	9591.12
COL	Sn61/N2581	9915.83	10222.11	9997.53	10192.61
COL	Sn64/N2584	10831.90	11264.91	10831.25	11252.27
COL	Sn65/N2585	10541.65	10974.32	10542.54	10998.38
COL	Sn66/N2586	9328.74	9494.23	9313.82	9499.05
COL	Sn71/N2591	10731.97	11191.95	10709.47	11107.68
COL	Sn72/N2592	10020.84	10576.89	9982.48	10575.21
COL	Sn83/N2603	14737.42	14834.13	14737.28	14815.35
COL	Sn87/N2607	15339.72	15428.55	15322.17	15546.73
COL	Sn89/N2609	**15699.72**	**15680.24**	**15698.58**	**15680.67**
COL	Sn90/N2610	15370.32	15561.02	15369.98	15651.70

4.1.2 Support Reactions of Existing Building Model Due to Wind Load

Table 4.4 summarises the support reactions of the existing building model due to wind load. It can be seen that the reaction forces for wind load with the wind flow direction of 270º, + CPE & + CPI are approximately equal to 270º, + CPE & - CPI. The same situation is observed for wind loads with 270º, - CPE & + CPI and 270º, - CPE & - CPI.

Table 4.4: Support Reactions of Existing Building Model Due to Wind Load.

Structure	**Node**	**Reaction force, Rz (kN)**			
		270º, + CPE, + CPI	**270º, + CPE, - CPI**	**270º, - CPE, + CPI**	**270º, - CPE, - CPI**
COL	Sn106/N2629	7.49	7.46	7.51	7.48
COL	Sn109/N2632	450.59	242.14	441.49	233.03
COL	Sn110/N2633	1489.11	770.30	1487.23	768.42
COL	Sn111/N2634	1727.46	1001.12	1721.99	995.66
COL	Sn112/N2635	-649.37	-210.46	-649.37	-210.47
COL	Sn113/N2636	911.21	734.66	909.73	733.18
COL	Sn114/N2637	-2119.77	-1345.86	-2118.59	-1344.68
COL	Sn118/N2641	-1093.32	-1342.74	-1094.03	-1343.45
COL	Sn60/N2580	-232.63	740.77	-241.33	732.08
COL	Sn61/N2581	-556.22	-478.86	-568.76	-491.40
COL	Sn64/N2584	-717.86	-492.28	-717.44	-491.86
COL	Sn65/N2585	-1061.01	-1215.51	-1060.14	-1214.65
COL	Sn66/N2586	1466.91	1602.63	1457.62	1593.34
COL	Sn71/N2591	-452.89	-970.47	-483.05	-1000.62
COL	Sn72/N2592	385.71	927.76	361.11	903.16
COL	Sn83/N2603	-257.26	-670.29	-257.63	-670.66
COL	Sn87/N2607	-231.08	-152.48	-231.89	-153.30
COL	Sn89/N2609	-73.88	-571.00	-75.58	-572.70
COL	Sn90/N2610	-898.38	-1114.8	-898.85	-1115.27

4.1.3 Support Reactions for Extended Building Model Due to Wind Load

Table 4.5 summarises the support reactions of the extended building model due to wind load. It can be seen that the reaction forces for wind load with the wind flow direction of 270º, + CPE & + CPI are approximately equal to 270º, + CPE & - CPI. The same situation is observed for wind loads with 270º, - CPE & + CPI and 270º, - CPE & - CPI.

Table 4.5: Support Reactions for Extended Building Model Due to Wind Load.

Structure	Node	Reaction force, Rz (kN)			
		270º, + CPE, + CPI	**270º, + CPE, - CPI**	**270º, - CPE, + CPI**	**270º, - CPE, - CPI**
COL	Sn106/N2629	8.65	8.66	8.67	8.68
COL	Sn109/N2632	580.26	297.68	570.2	287.62
COL	Sn110/N2633	1908.23	979.95	1904.14	975.86
COL	Sn111/N2634	2175.53	1269.10	2163.77	1257.34
COL	Sn112/N2635	-782.85	-245.31	-783.80	-246.26
COL	Sn113/N2636	1103.78	893.39	1101.31	890.92
COL	Sn114/N2637	-2636.65	-1625.51	-2637.69	-1668.99
COL	Sn118/N2641	-1482.70	-1767.83	-1483.62	-1768.75
COL	Sn60/N2580	-271.61	1017.52	-290.29	998.85
COL	Sn61/N2581	-769.04	-627.34	-793.44	-651.73
COL	Sn64/N2584	-960.49	-649.82	-961.36	-650.69
COL	Sn65/N2585	-1408.97	-1605.41	-1407.79	-1604.23
COL	Sn66/N2586	1906.25	2126.91	1886.36	2107.01
COL	Sn71/N2591	-500.94	-1220.96	-530.95	-1250.97
COL	Sn72/N2592	531.07	1272.48	479.93	1221.34
COL	Sn83/N2603	-370.57	-908.29	-370.76	-908.48
COL	Sn87/N2607	-276.01	-157.57	-299.42	-180.98
COL	Sn89/N2609	-107.93	-760.97	-109.46	-762.49
COL	Sn90/N2610	-1175.17	-1454.24	-1175.63	-1454.70

4.2 Comparison of Support Reactions

4.2.1 Ultimate Limit State

In the comparative study, the difference between the support reactions of the columns for the existing and extended building model was identified. The comparison was made for all types of ULS combinations, as presented in Table 4.6, Table 4.7, Table 4.8 and Table 4.9. From the tabulated data, it is obvious that the reaction forces of extended building for all combinations are higher than that of the existing building model. The difference in support reactions between the existing and extended building models ranges from 0.89 kN to 1078.73 kN, and the percentage difference ranges between 0.18 % to 12%. The discrepancies between the two models are primarily because the extensions increase the total weight of the building, and the columns are required to bear a greater self-weight of the building, which contributes to higher reaction forces in the extended building model. Apart from that, it is worth mentioning that the critical column was found at N2609 for both cases.

Table 4.6: Comparison of Existing and Extended Building Models Under ULS1.

Structure	Node	Rz (kN)		Difference (kN)	Difference (%)
		Existing Building	With Extension		
COL	Sn106/N2629	377.59	378.49	0.90	0
COL	Sn109/N2632	5682.89	5791.20	108.31	2
COL	Sn110/N2633	10745.27	11121.41	376.14	4
COL	Sn111/N2634	8548.78	8900.92	352.14	4
COL	Sn112/N2635	2337.62	2426.09	88.47	4
COL	Sn113/N2636	3372.04	3525.87	153.83	5
COL	Sn114/N2637	8605.55	8788.12	182.57	2
COL	Sn118/N2641	11498.10	11523.08	24.98	0
COL	Sn60/N2580	8403.62	8587.41	183.79	2
COL	Sn61/N2581	9736.92	9915.83	178.91	2
COL	Sn64/N2584	10705.57	10831.90	126.33	1
COL	Sn65/N2585	10194.60	10541.65	347.05	3
COL	Sn66/N2586	8946.81	9328.74	381.93	4
COL	Sn71/N2591	10750.86	10731.97	18.89	0
COL	Sn72/N2592	9897.83	10020.84	123.01	1
COL	Sn83/N2603	14608.81	14737.42	128.61	1
COL	Sn87/N2607	15209.48	15339.72	130.24	1
COL	Sn89/N2609	15611.11	15699.72	88.61	1
COL	Sn90/N2610	14966.18	15370.32	404.14	3

Table 4.7: Comparison of Existing and Extended Building Models Under ULS2.

Structure	Node	Rz (kN)		Difference (kN)	Difference (%)
		Existing Building	With Extension		
COL	Sn106/N2629	377.58	378.49	0.91	0
COL	Sn109/N2632	5526.55	5579.27	52.72	1
COL	Sn110/N2633	10206.16	10425.20	219.04	2
COL	Sn111/N2634	8004.03	8221.10	217.07	3
COL	Sn112/N2635	2666.79	2829.24	162.45	6
COL	Sn113/N2636	3239.63	3368.08	128.45	4
COL	Sn114/N2637	9185.98	10014.64	828.66	9
COL	Sn118/N2641	11311.03	12209.23	898.20	8
COL	Sn60/N2580	9133.67	9354.26	220.59	2
COL	Sn61/N2581	9794.94	10222.11	427.17	4
COL	Sn64/N2584	10874.75	11264.91	390.16	4
COL	Sn65/N2585	10078.72	10974.32	895.60	9
COL	Sn66/N2586	9048.59	9494.23	445.64	5
COL	Sn71/N2591	10362.68	11191.95	829.27	8
COL	Sn72/N2592	10304.36	10576.89	272.53	3
COL	Sn83/N2603	14299.03	14834.13	535.10	4
COL	Sn87/N2607	15238.27	15428.55	160.13	1
COL	Sn89/N2609	15268.42	15680.24	441.97	3
COL	Sn90/N2610	14803.87	15561.02	757.15	5

Table 4.8: Comparison of Existing and Extended Building Models Under ULS3.

Structure	Node	Rz (kN)		Difference (kN)	Difference (%)
		Existing Building	With Extension		
COL	Sn106/N2629	377.61	378.50	0.89	0
COL	Sn109/N2632	5676.07	5783.66	107.59	2
COL	Sn110/N2633	10743.86	11118.33	374.47	3
COL	Sn111/N2634	8544.68	8892.10	347.42	4
COL	Sn112/N2635	2337.61	2425.38	87.77	4
COL	Sn113/N2636	3370.93	3524.02	153.09	5
COL	Sn114/N2637	8606.43	8787.34	180.91	2
COL	Sn118/N2641	11497.57	11522.39	24.82	0
COL	Sn60/N2580	8397.10	8573.41	176.31	2
COL	Sn61/N2581	9727.52	9997.53	270.01	3
COL	Sn64/N2584	10705.88	10831.25	125.37	1
COL	Sn65/N2585	10195.25	10542.54	347.29	3
COL	Sn66/N2586	8939.84	9313.82	373.98	4
COL	Sn71/N2591	10728.25	10709.47	18.78	0
COL	Sn72/N2592	9879.38	9982.48	103.10	1
COL	Sn83/N2603	14608.53	14737.28	128.75	1
COL	Sn87/N2607	15208.86	15322.17	113.31	1
COL	Sn89/N2609	15609.83	15698.58	88.75	1
COL	Sn90/N2610	14965.83	15369.98	404.15	3

Table 4.9: Comparison of Existing and Extended Building Models Under ULS4.

Structure	Node	Rz (kN)		Difference (kN)	Difference (%)
		Existing Building	With Extension		
COL	Sn106/N2629	377.59	378.50	0.91	0
COL	Sn109/N2632	5519.73	5556.01	36.28	1
COL	Sn110/N2633	10204.75	10430.23	225.48	2
COL	Sn111/N2634	7999.93	8269.27	269.34	3
COL	Sn112/N2635	2666.79	2813.22	146.43	5
COL	Sn113/N2636	3238.52	3398.04	159.52	5
COL	Sn114/N2637	9186.87	10265.60	1078.73	12
COL	Sn118/N2641	11310.50	12335.10	1024.60	9
COL	Sn60/N2580	9127.15	9591.12	463.97	5
COL	Sn61/N2581	9785.54	10192.61	407.07	4
COL	Sn64/N2584	10875.07	11252.27	377.20	3
COL	Sn65/N2585	10079.37	10998.38	919.01	9
COL	Sn66/N2586	9041.63	9499.05	457.42	5
COL	Sn71/N2591	10340.06	11107.68	767.62	7
COL	Sn72/N2592	10285.92	10575.21	289.29	3
COL	Sn83/N2603	14298.76	14815.35	516.59	4
COL	Sn87/N2607	15236.99	15546.73	278.92	2
COL	Sn89/N2609	15267.80	15680.67	443.68	3
COL	Sn90/N2610	14803.52	15651.70	848.18	6

4.2.2 Wind Load

The following tables display the comparison of the support reactions for existing and extended building models due to the wind load. From the data analysis, it was found that the difference in the reaction forces varies from 1.16 kN to 524.28 kN, with a percentage difference ranging from 3.34 % to 46.09 %. Generally, higher reaction forces were detected in the extended building, possibly due to the increased height of the overall building.

Meanwhile, the disparity of support reactions attributed is likely to contribute to the difference in reactions under ULS to some extent.

Table 4.10: Comparison of Existing and Extended Building Models Under Wind Load of 270º, + CPE, + CPI.

Structure	Node	Rz (kN)		Difference (kN)	Difference (%)
		Existing Building	With Extension		
COL	Sn106/N2629	7.49	8.65	1.16	15
COL	Sn109/N2632	450.59	580.26	129.67	29
COL	Sn110/N2633	1489.11	1908.23	419.12	28
COL	Sn111/N2634	1727.46	2175.53	448.07	26
COL	Sn112/N2635	-649.37	-782.85	133.48	21
COL	Sn113/N2636	911.21	1103.78	192.57	21
COL	Sn114/N2637	-2119.77	-2636.65	516.88	24
COL	Sn118/N2641	-1093.32	-1482.70	389.38	36
COL	Sn60/N2580	-232.63	-271.61	38.98	17
COL	Sn61/N2581	-556.22	-769.04	212.82	38
COL	Sn64/N2584	-717.86	-960.49	242.63	34
COL	Sn65/N2585	-1061.01	-1408.97	347.96	33
COL	Sn66/N2586	1466.91	1906.25	439.34	30
COL	Sn71/N2591	-452.89	-500.94	48.05	11
COL	Sn72/N2592	385.71	531.07	145.36	38
COL	Sn83/N2603	-257.26	-370.57	113.31	44
COL	Sn87/N2607	-231.08	-276.01	44.93	19
COL	Sn89/N2609	-73.88	-107.93	34.05	46
COL	Sn90/N2610	-898.38	-1175.17	276.79	31

Table 4.11: Comparison of Existing and Extended Building Models Under Wind Load of 270º, + CPE, - CPI.

Structure	Node	Rz (kN)		Difference (kN)	Difference (%)
		Existing Building	With Extension		
COL	Sn106/N2629	7.46	8.66	1.20	16
COL	Sn109/N2632	242.14	297.68	55.54	23
COL	Sn110/N2633	770.30	979.95	209.65	27
COL	Sn111/N2634	1001.12	1269.10	267.98	27
COL	Sn112/N2635	-210.46	-245.31	34.85	17
COL	Sn113/N2636	734.66	893.39	158.73	22
COL	Sn114/N2637	-1345.86	-1625.51	279.65	21
COL	Sn118/N2641	-1342.74	-1767.83	425.09	32
COL	Sn60/N2580	740.77	1017.52	276.75	37
COL	Sn61/N2581	-478.86	-627.34	148.48	31
COL	Sn64/N2584	-492.28	-649.82	157.54	32
COL	Sn65/N2585	-1215.51	-1605.41	389.90	32
COL	Sn66/N2586	1602.63	2126.91	524.28	33
COL	Sn71/N2591	-970.47	-1220.96	250.49	26
COL	Sn72/N2592	927.76	1272.48	344.72	37
COL	Sn83/N2603	-670.29	-908.29	238.00	36
COL	Sn87/N2607	-152.48	-157.57	5.09	3
COL	Sn89/N2609	-571.00	-760.97	189.97	33
COL	Sn90/N2610	-1114.80	-1454.24	339.44	30

Table 4.12: Comparison of Existing and Extended Building Models Under Wind Load of 270º, - CPE, + CPI.

Structure	Node	Rz (kN)		Difference (kN)	Difference (%)
		Existing Building	With Extension		
COL	Sn106/N2629	7.51	8.67	1.16	15
COL	Sn109/N2632	441.49	570.20	128.71	29
COL	Sn110/N2633	1487.23	1904.14	416.91	28
COL	Sn111/N2634	1721.99	2163.77	441.78	26
COL	Sn112/N2635	-649.37	-783.80	134.43	21
COL	Sn113/N2636	909.73	1101.31	191.58	21
COL	Sn114/N2637	-2118.59	-2637.69	519.10	25
COL	Sn118/N2641	-1094.03	-1483.62	389.59	36
COL	Sn60/N2580	-241.33	-290.29	48.96	20
COL	Sn61/N2581	-568.76	-793.44	224.68	40
COL	Sn64/N2584	-717.44	-961.36	243.92	34
COL	Sn65/N2585	-1060.14	-1407.79	347.65	33
COL	Sn66/N2586	1457.62	1886.36	428.74	29
COL	Sn71/N2591	-483.05	-530.95	47.90	10
COL	Sn72/N2592	361.11	479.93	118.82	33
COL	Sn83/N2603	-257.63	-370.76	113.13	44
COL	Sn87/N2607	-231.89	-299.42	67.53	29
COL	Sn89/N2609	-75.58	-109.46	33.88	45
COL	Sn90/N2610	-898.85	-1175.63	276.78	31

Table 4.13: Comparison of Existing and Extended Building Models Under Wind Load of 270º, - CPE, - CPI.

Structure	Node	Rz (kN)		Difference (kN)	Difference (%)
		Existing Building	With Extension		
COL	Sn106/N2629	7.48	8.68	1.20	16
COL	Sn109/N2632	233.03	287.62	54.59	23
COL	Sn110/N2633	768.42	975.86	207.44	27
COL	Sn111/N2634	995.66	1257.34	261.68	26
COL	Sn112/N2635	-210.47	-246.26	35.79	17
COL	Sn113/N2636	733.18	890.92	157.74	22
COL	Sn114/N2637	-1344.68	-1668.99	324.31	24
COL	Sn118/N2641	-1343.45	-1768.75	425.30	32
COL	Sn60/N2580	732.08	998.85	266.77	36
COL	Sn61/N2581	-491.40	-651.73	160.33	33
COL	Sn64/N2584	-491.86	-650.69	158.83	32
COL	Sn65/N2585	-1214.65	-1604.23	389.58	32
COL	Sn66/N2586	1593.34	2107.01	513.67	32
COL	Sn71/N2591	-1000.62	-1250.97	250.35	25
COL	Sn72/N2592	903.16	1221.34	318.18	35
COL	Sn83/N2603	-670.66	-908.48	237.82	35
COL	Sn87/N2607	-153.30	-180.98	27.68	18
COL	Sn89/N2609	-572.70	-762.49	189.79	33
COL	Sn90/N2610	-1115.27	-1454.70	339.43	30

4.3 Evaluation of Support Reactions

From the findings, it is possible to ascertain that the increment in wind load is one of the most important aspects to be considered while extending the building vertically. This is evident by the substantial percentage difference (ranging from 3.34 % to 46.09 %) of the support reactions for the extended building under the wind load impact compared to the ULS load combinations. Theoretically, wind load affects the wind moment at the base of the building and consequently on the tensile stresses there. In this research, the lightweight module was adopted for the extension, which led to a minor rise in the overall compressive stresses but influenced more on the tensile strength of the stabilising components due to the increased wind loads associated with increased building height. As a result of the increasing wind load, overturning uplift is likely to happen on the lightweight structure. In response to the sharp increase of the reactions due to wind loads, it is possible to convert the existing structural stability system or install additional stability components.

4.4 Technical Challenges Associated with Vertical Extension

4.4.1 Existing Building Condition

One of the first steps of a vertical extension is evaluating the existing structure. The issues mostly arise from a lack of knowledge to complete a job, particularly during the early design. Lack of knowledge regarding the operating infrastructure and space constraints are among issues that arise while planning for extension projects. Untimely information complicates the design process. A thorough examination of the existing building is needed to evaluate the existing building conditions and the method to execute. As stated in the literature review, a range of procedures and tests may be used to characterise the technical properties of the existing building. It is worth mentioning that these procedures are not only useful when there is a lack of relevant information but also when the information is available and has to be verified. This is significant because the building may have defects or damage over time, affecting its overall structural stability. In this situation, on-site assessment and inspections are required to assess the existing building condition to justify its life extension. However, the intrusive investigations often involve destructive tests coupled with the non-destructive test to assess reinforced concrete and rebars' mechanical and physical characteristics. For instance, extraction or coring of the concrete specimens, rebar exposure, and deep trial pit to explore foundations are some procedures requiring breaking down of material. Undoubtedly, the structural investigations will cause interruption to the residents. Thus, it is necessary to determine the structural risks in early-stage and plan for contingencies.

4.4.2 Extension Concept

The practicality of vertical extension depends greatly on the characteristics of the existing building itself. As observed in the present study, introducing additional floors to a building with flat roofs is both aesthetically and technically feasible. The optimum additional space that can be constructed must be considered while conceiving expansion. Besides, the increase in height due to extension is also associated with natural lighting problems. The geometrical layout of the extension units must allow for the preservation of natural light in the surrounding environments. Nevertheless, it is worth noting that the additional weight has to be carried by the load-bearing systems of the existing building and that the existing roof slab will not support the extra loadings due to the extension. Therefore, when planning the floor plan for the additional levels, the orientation and arrangement of the extension units are determined by the position of the load-bearing system below.

4.4.3 Constructability and Installation Methods

The majority of the vertical expansion projects happen in dense urban areas with limited space for on-site construction. Additionally, vertical extensions take place at relatively high altitudes, making the construction process more challenging. It can be said that construction management plays a significant role in ensuring a smooth construction process. Particularly, sufficient safeguards are required for the construction workers while working at the high levels. Appropriate measures must be taken to prevent the structural materials or objects from falling from a great height which may cause undesirable injuries or fatalities. Due to space and transportation constraints, engineers have to plan the building site carefully. Furthermore, the construction materials and equipment have to be supplied on time to avoid delays or deterioration of the traffic around the construction site. This is essential because the construction works generally affect the access into and from the existing building, which causes disturbance to local inhabitants.

It is preferable to have a fast construction while minimising the on-site construction duration. Findings revealed that the use of prefabricated components is suitable for building extension. This is mainly because off-site manufacturing achieves rapid construction while ensuring the quality of elements. Numerous vertical extension modules can be built simultaneously in the factory and subsequently delivered to the site, lifted and arranged in their designated location. Modules may be delivered at any time to suit local circumstances. As such, the existing building can be transformed while it is still partly inhabited. In some instances, it may not be required for the residents to vacate the premises, eliminating the need for temporary shelter. Briefly, vertical extension of a building requires well-planned and well-coordinated design, production, and site installation works.

4.4.4 Installation of Building Services

Another aspect that required extra scrutiny was installing building services and ventilation shafts. The primary services include heat ventilation, lighting, electricity, plumbing, vertical mobility communication and telecommunications. Notably, the installations of the existing building are typically constructed without consideration of future expansion. Thus, it is possible that those in the extension are not always able to connect to the current ones. Indeed, the installation of building services in the extension can be planned. The additional floors and the existing building function with two independent installations, or they can be connected and combined into one. In some instances, the existing shafts are big enough to accommodate the additional installations, while new shafts are required for others. The same is true for elevators. The additional levels must be accessible by stair or elevator. The existing elevator shaft can be expanded regardless of whether the extension has a similar layout. Nevertheless, installations of the building services for the extension must be designed correctly and in compliance with the national requirements for new construction in terms of energy usage, ventilation, water supply and other standards.

4.4.5 Building Retrofitting

Building retrofitting or refurbishment is necessary when the structural system does not have sufficient capacity to bear the extra loadings; or when there are defects in the existing building that affect the building's structural strength and stability. Building retrofitting is often complex, risky and difficult, especially when structural modifications are included. In general, building retrofitting requires specialised knowledge for integration under highly unpredictable situations. When remediating the existing building, more measures need to be taken because they often impact construction methods and the structure's design. Moreover, another crucial aspect that increases the uncertainty of the design of building retrofitting is the building services of the existing building. Designers are compelled to make assumptions regarding the service routing due to hidden elements such as electrical wires and piping. As a consequence of the erroneous route design, modifications in design are required from time to time throughout the construction stage. Apart from that, residents must be considered during the design and construction phases as the structural strengthening works to influence the local inhabitants the most.

4.4.6 Fire Protection Requirements

As a result of increased population and building height, a greater level of fire protection is sometimes needed for the building. It is vital to justify the changes in fire-resistance ratings as this may substantially impact the feasibility of vertical extension. The firefighting strategies and structural fire resistance need improvement due to the increased evacuation periods and more difficult firefighting operations. This necessitates fire safety enhancements, including the firefighting access, fire sprinkler system, smoke control, compartmentation, and evacuation routes.

4.4.7 Accessibility Issues

The accessibility and egress issues have to be considered during the design of the vertical extension. As a consequence of the rising population, the current egress routes will receive a greater passenger load. Due to the increased traffic load, a new egress route is sometimes needed. Setting aside the traffic impacts and accessibility issues, another issue that must be considered is the availability of parking spaces for the residents. The research found that building expansion should start with parking space planning; it must first be decided how many parking places or car parks can be established on the site in a non-disruptive manner to the living environment.

4.5 Carbon Impact due to Vertical Extension

4.5.1 Estimation of Embodied Carbon with Revit Software

Table 4.14 presents the overall carbon emissions resulting from the vertical extension. A bar chart was created, as shown in, Figure 4.3, for a clearer presentation of the results. Based on computed results, 431.373 tCO_2e embodied carbon was generated from the building associated with the vertical extension. Findings revealed that the carbon emissions generated during the material production stage accounted for most of the overall emissions, contributing to 81.8 % of the total emission. The carbon emitted due to the replacement of the structural materials came in second, accounting for 8.9 % of the total emissions, followed by construction, transportation and end of life stages which occupy a smaller portion; that is 5.2 %, 2.5 % and 1.6 %, respectively. The results indicate that more CO_2 emissions were generated in the manufacturing and processing of the building materials. This result differed from other studies, which opined that a building's use phase generally contributes to more carbon emissions. This is mainly because Revit software only considers CO_2 emissions to replace structural materials (B4) throughout the building's operational stage. To clarify, the carbon emissions due to normal use of the building (B1), maintenance (B2), repair (B3), refurbishment (B5), operational energy during occupancy (B6), as well as the carbon impact of water use (B7) were not included in the computation of CO_2 emission in this study. Module B4 covers the carbon emission from the production and transportation of structural materials. As shown in Figure 4.3, only gypsum plasterboard required replacement throughout the building's lifecycle.

Furthermore, it can be seen that different structural materials correspond to different embodied carbon emissions. Results show that the embodied carbon for brick, cold-formed steel, concrete precast block, and gypsum plasterboard were 81.040 tCO_2e, 75.485 tCO_2e, 197.362 tCO_2e and 77.486 tCO_2e, respectively. Obviously, EC of concrete accounts for a significant portion of total embodied CO_2; that is 45.8 %. Concrete was the main CO_2 contributor because the designed extension module was mainly composed of concrete. Specifically, the concrete volume used for an extension module was 22.34 m^3, amounting to 68.6 % of the total volume of material.

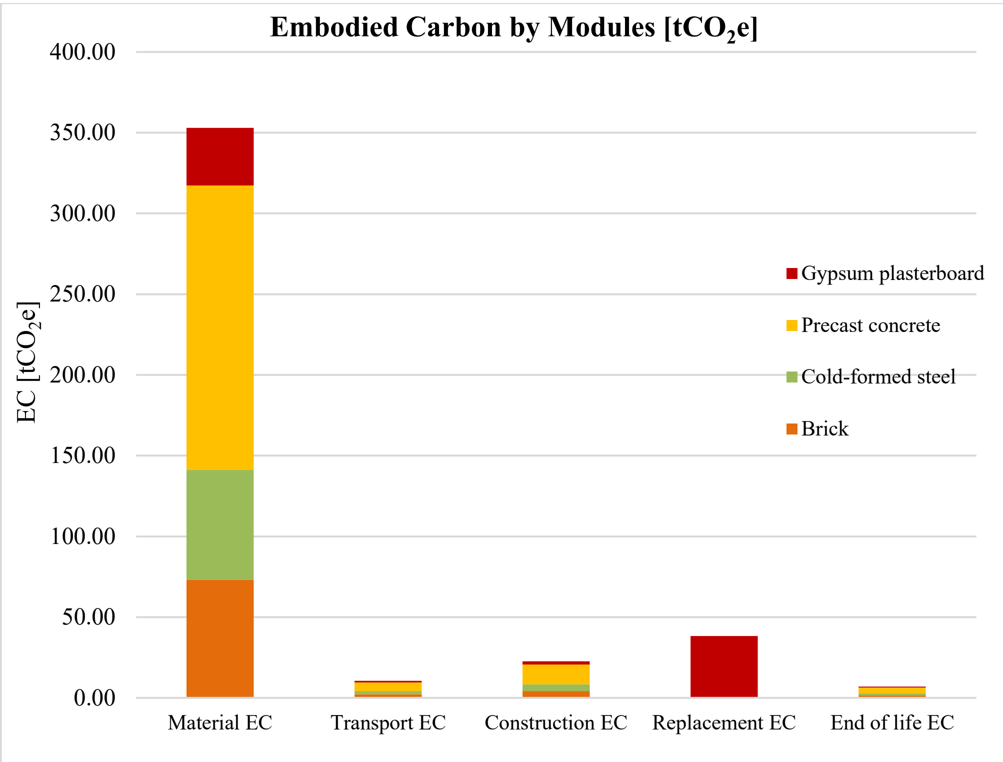


Figure 4.3: Results of Embodied Carbon Due to Vertical Extension.

Table 4.14: Carbon Emissions Due to Vertical Extension Computed by Revit Software.

	Embodied Carbon, EC (tCO_2e)					
Material	**Overall material EC**	**Overall transport EC**	**Overall construction EC**	**Replacement over 60 Years**	**Overall end of life EC**	**Total EC (tCO_2e)**
Brick	73.119	2.194	4.265	–	1.462	81.040
Cold-Formed Steel	67.952	2.039	4.136	–	1.359	75.485
Concrete - Precast Block 40/50	176.325	5.290	12.221	–	3.527	197.362
Gypsum Plasterboard	35.534	1.050	2.000	38.202	0.700	77.485
	Total EC_{A1-A5} = **386.123**					ΣEC = **431.373**

4.5.2 Estimation of Embodied Carbon Based on IStructE Guideline

The EC of different materials computed based on IStructE guide were tabulated in Table 4.15. Figure 4.4 depicts the contribution CO_2 of each structural material by modules. Carbon emissions for different structural materials were estimated for production (Modules A1 – A3) and construction stages (Module A4 – A5). The total carbon emissions from the vertical extension were 384.257 tCO_2e, with the highest emissions generated during the production stage (335.155 tCO_2e), followed by the construction stage (49.101 tCO_2e). Among the CO_2 emissions associated with materials production, precast concrete block contributes the highest, with 62.6 %, whereas other materials accounted for 37.4 %. In terms of carbon emissions during the construction stage, 84.1 % was generated from the construction activities (A5a and A5w), while transportation (A4) was 15.9 %. It is worth noting that the site activities (A5a) emissions involve on-site energy usage and fuel use, which require site-specific information for accurate computation. In the absence of the site-specific data for this research, A5a emissions were estimated based on the rating (1400 $kgCO_2e$ per 100,000 pounds construction cost) provided by IStructE. The preliminary calculations assumed a total construction cost of RM 5,000,000.00 for the vertical extension, which was estimated based on the property type and gross floor area of 1728 m^2.

Table 4.15: Embodied Carbon of Structural Materials of Extension Module Based on IStrutE Guideline.

	EC (tCO_2e)				**Total**
Material	**A1 – A3**	**A4**	**A5w**	**A5a**	**A1 – A5w**
Brick	61.803	1.451	17.119		80.372
Cold Formed Steel	34.819	0.112	0.353		35.285
Concrete - Precast Block 40/50	209.967	5.898	2.371	12.658	218.236
Gypsum Plasterboard	28.566	0.366	8.773		37.705
Total	335.155	7.827	28.616	12.658	371.599
Grand total				**384.257**	

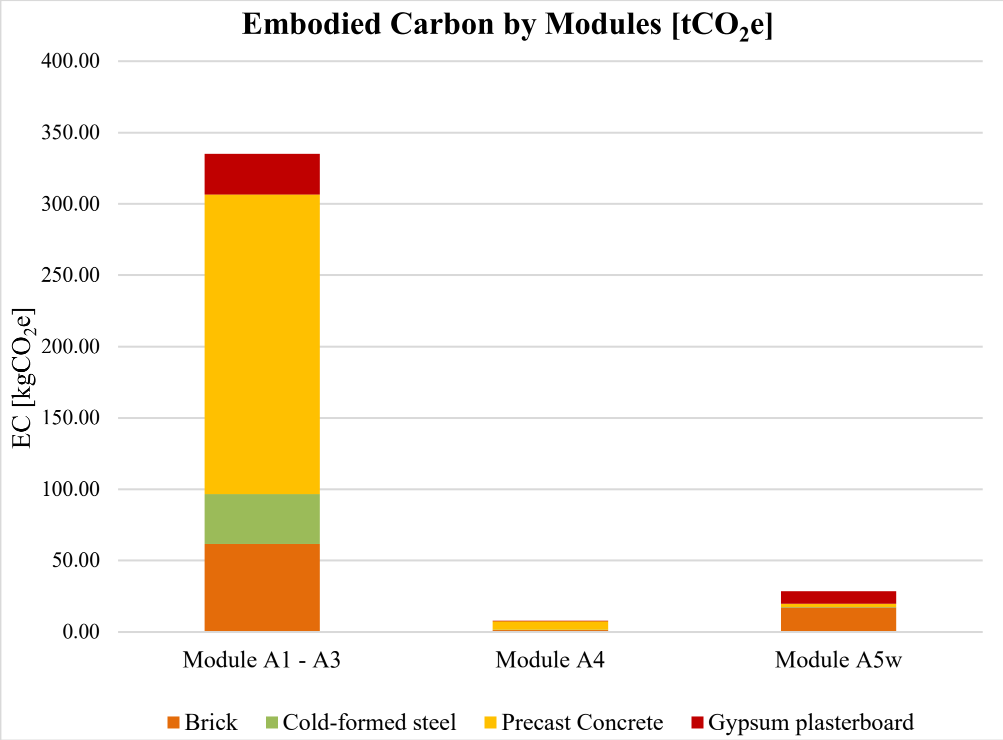


Figure 4.4: Results of Embodied Carbon by Modules Due to Vertical Extension.

4.6 Carbon Impact Due to Demolition and Reconstruction

4.6.1 Estimation of Embodied Carbon with Revit Software

The CO_2 emissions generated during demolition and reconstruction were evaluated separately. The CO2 emissions were examined from the waste brick wall, waste concrete, and gypsum plasterboard in the demolition phase. The embodied carbon of the waste materials was tabulated in Table 4.16. Findings indicated that a total volume of 16075.69 m^3 of waste materials was created during demolition. The assessment of EC due to building demolition was performed with respect to the end-of-life stage of the building. The total CO_2 emissions during the demolition were 114.708 tCO_2e. Particularly, the percentage of CO_2 emissions from the structural materials was 12.4 % brick, 75.7 % reinforced concrete, and 11.9 % gypsum plasterboard. Waste RC has the highest level of CO_2 mainly because RC was the primary material that formed the structural framing of the existing building. Notably, RC accounted for 79.8 % of the total volume of waste materials.

Table 4.16: Carbon Emissions During Demolition of Existing Structure.

Material	Overall end of life EC (tCO_2e)
Brick	14.276
Concrete in situ – RC 30/37	86.832
Gypsum Plasterboard	13.599
Total	114.708

Estimation of the carbon impact in Revit of the new construction follows the same method as in vertical extension, which generally covers the material EC, transportation EC, construction EC, replacement EC, and end of life EC. The corresponding results of different structural materials are summarised in Table 4.17. A bar chart was generated for a better presentation of the results, as shown in Figure 4.5. The results show that the carbon emissions were most influenced by the production of materials, with RC concrete as the major source (82.1 %) of the CO_2 emissions. The high value of concrete emissions was because the frame sections and flooring of the new construction were predominately made up of RC concrete. In addition, the production of the raw material of concrete – cement, was the largest contributor to CO_2 emissions. By considering both the demolition of the existing building and reconstruction, the total emissions generated were found to be 11006.218 tCO_2e.

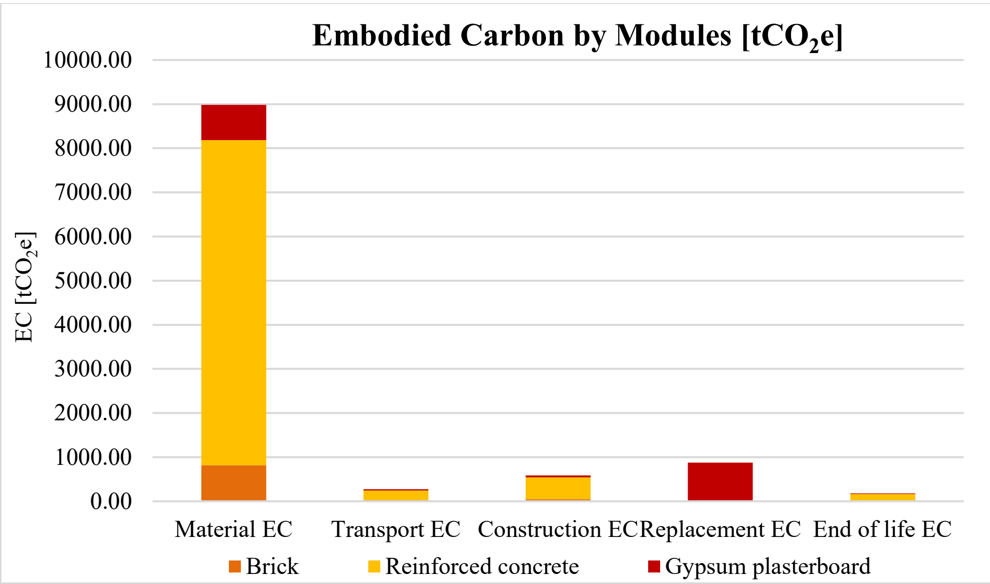


Figure 4.5: Results of Embodied Carbon Due to New Construction.

Table 4.17: Carbon Emissions During New Construction.

Material	Overall material EC	Overall transport EC	Overall construction EC	Replacement over 60 Years	Overall end of life EC	Total EC (tCO_2e)
	Embodied Carbon, EC (tCO_2e)					
Brick	814.451	24.434	47.510	–	16.289	902.683
Concrete in situ – RC 30/37	7371.819	221.546	491.455	–	147.436	8232.255
Gypsum Plasterboard	793.290	23.799	45.331	878.286	15.866	1756.572
	Total EC_{A1-A5} = **9833.633**					ΣEC = **10891.510**

4.6.2 Estimation of Embodied Carbon Based on IStructE Guide

The CO_2 emissions arising during demolition were computed based on 3.4 $kgCO_2e/m^2$ GIA rating. The gross internal area of the existing building obtained from SCIA Engineer was 40068.32 m^2. Thus, the level of CO_2 generated during the demolition of the existing structure was 136.23 tCO_2e. Apart from that, the carbon impact of the new construction was evaluated for Modules A1 – A5w, and the results were shown in Table 4.18. As shown in Figure 4.4, a bar chart was generated for a clearer illustration of the data. Results show that 12230.653 tCO_2e emissions were released while constructing a new residential building. A similar trend is observed in which the production phase of material reported the highest share (88.6 %) of emissions. Besides, it is worth mentioning that the embodied carbon of the reinforced concrete was obtained through the derivation of emissions from unreinforced concrete and steel reinforcement. This is because the embodied carbon factor for the proposed reinforced concrete was not readily available. The rebar weight of 1959.287 tons was obtained based on the total volume of concrete by assuming 90 kg/m^3 of concrete. For the estimated EC by module A5a, the total construction cost of RM 48,000,000 was considered for the new construction with a GIA of 44040.32 m^2. Withal, the emissions from site activities are approximately 121.517 tCO_2e.

Table 4.18: Carbon Emissions During New Construction.

<table>
<tr><th></th><th colspan="4">EC (tCO_2e)</th><th rowspan="2">Total
A1 – A5w</th></tr>
<tr><th>Material</th><th>A1 – A3</th><th>A4</th><th>A5w</th><th>A5a</th></tr>
<tr><td>Brick</td><td>688.406</td><td>16.160</td><td>190.685</td><td rowspan="4">121.517</td><td>895.252</td></tr>
<tr><td>Concrete in situ C30/37</td><td>5605.739</td><td>272.123</td><td>363.448</td><td>6241.310</td></tr>
<tr><td>Gypsum Plasterboard</td><td>647.584</td><td>8.302</td><td>198.875</td><td>854.761</td></tr>
<tr><td>Steel reinforcement</td><td>3898.982</td><td>9.796</td><td>209.034</td><td>4117.813</td></tr>
<tr><td>Total</td><td>10840.711</td><td>306.382</td><td>962.042</td><td>121.517</td><td>12109.136</td></tr>
<tr><td colspan="4">Grand total</td><td colspan="2">12230.653</td></tr>
</table>

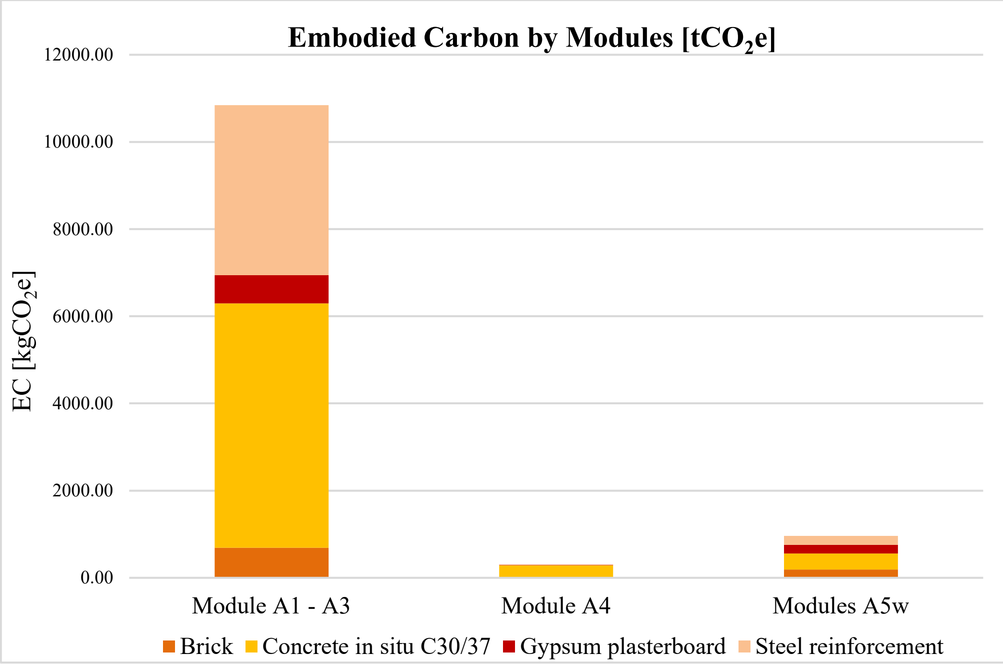


Figure 4.6: Carbon Emissions by Modules During New Construction.

4.7 Comparison of Embodied Carbon Results from Revit and IStructE Guideline

From the findings, it is noticed that the main difference between Revit software and IStructE in computing the carbon emissions is the coverage of the lifecycle stages. Particularly, Revit software calculates the EC from modules A-C, whereas IStructE focuses only on modules A1 – A5. In order to make the carbon impact of the two methods comparable, the lifecycle modules that were taken into the EC estimation must be consistent for both computation methods. Thus, only modules A1 – A5 were examined in the comparative study. Table 4.19 shows the comparison of carbon impact computed from Revit and IStructE.

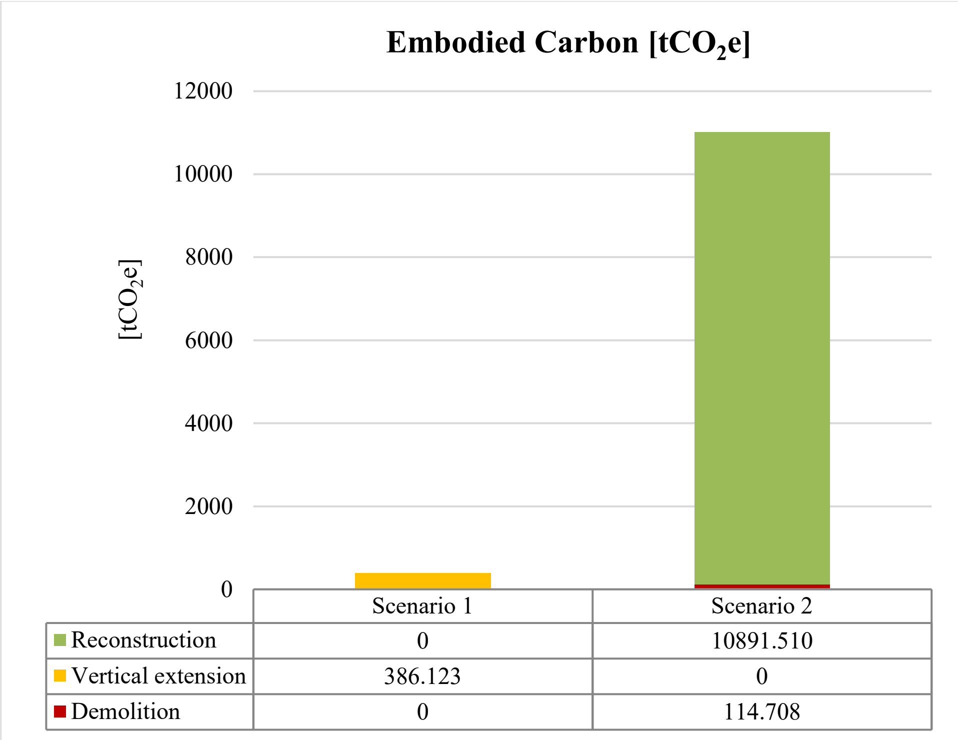
Table 4.19: Comparison of Carbon Impact Obtained from Revit and IStructE.

Scenarios	Embodied carbon (tCO_2e)		Difference (tCO_2e)	Difference (%)
	Revit	IStructE		
Vertical Extension	386.123	384.257	1.866	0.5
Demolition	114.708	136.23	21.522	18.8
New construction	9833.633	12230.653	2397.02	24.4

The tabulated data shows that the difference in the embodied carbon obtained from the two methods ranges from 1.866 tCO_2e to 2397.02 tCO_2e, and the percentage difference ranges from 0.5 % to 24.4 %. This difference in the carbon impact is primarily due to the carbon factors or coefficients used for different structural materials while undertaking CO_2 estimations. Moreover, a high value of the difference (24.4 %) was observed for the EC of new construction. Through the analysis, it was found that the production phase accounts for the majority of the discrepancy. This is likely to relate to the different ways to assess the reinforced concrete's carbon impact. Revit software estimates the CO_2 emissions of the RC as a whole, whereas IStructE breaks down the RC into unreinforced concrete and steel reinforcement during estimation.

4.8 Comparison of Carbon Emissions of Different Scenarios

In this study, vertical extension (Scenario 1) and demolition & reconstruction (Scenario 2) were compared based on the results obtained from Revit software, as Revit provide a more comprehensive analysis of the lifecycle carbon footprint. Figure 4.7 demonstrates the carbon emissions generated by various activities in each scenario. As illustrated in Figure 4.7, carbon emissions from Scenario 2 (11006.218 tCO_2e) were higher than in Scenario 1 (386.123 tCO_2e). In Scenario 2, the new construction resulted in the highest CO_2 emissions (99 % of the total), accounting for 10891.510 tCO_2e emissions. The carbon impact of the vertical extension was smaller than demolition and new construction. This was likely because the vertical extension utilised the existing building stock, eliminating the construction of load-bearing structures, thus avoiding significant quantities of carbon emissions. In contrast, demolition followed by redevelopment generally means that the whole building was rebuilt, where massive material consumption and construction works are involved, contributing to increased environmental consequences. It can be concluded that vertical extension provides additional living space with minimal carbon impact compared to reconstruction.



	Scenario 1	Scenario 2
Reconstruction	0	10891.510
Vertical extension	386.123	0
Demolition	0	114.708

Figure 4.7: Results of EC (in tCO_2e) of Different Scenarios.

4.9 Comparison of Embodied Carbon to SCORS

The carbon footprint assessment based on SCORS rating was performed based on the anticipated carbon emissions from modules A1 – A5. During the analysis, the carbon footprint was obtained by dividing the embodied carbon (of IStructE publication) by the GIA of the building. For the vertical extension, 1728 m^2 (78 m^2/unit) was applied. For the demolition of the existing building, 40068.324 m^2 was adopted. In the case of new construction, a GIA of 44040.320 m^2 was applied. The carbon footprint of the two scenarios is presented in Figure 4.8 using the SCORS grading scheme. As shown in Figure 4.8, Scenario 1 has a C rating (222.371 $kgCO_2e/m^2$) whereas Scenario 2 has a D rating (281.115 $kgCO_2e/m^2$). It can be inferred that vertical extension is a more carbon-efficient alternative than destructing and rebuilding a structure.

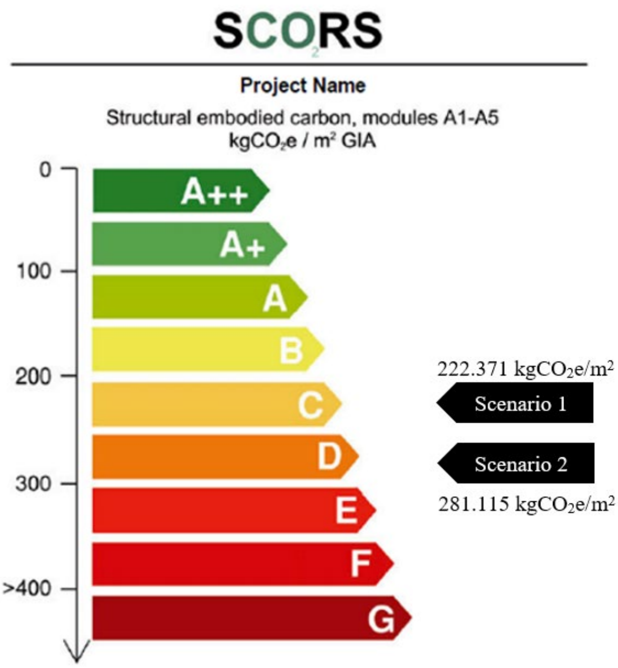


Figure 4.8: Structural Embodied Carbon Rating of the Two Scenarios.

4.10 Summary

In summary, both the existing and extended building models are evaluated and compared in terms of the reaction forces under the ultimate limit state and wind load, respectively. The percentage differences in the support reactions of the existing and extended building models were calculated. Findings revealed that the extended building model has larger reaction forces due to the increase in the overall weight of the building and greater wind loads contributed by the increment in the building's height. Next, the technical challenges associated with vertical extension were discussed in detail. Furthermore, the carbon emission arising from the vertical extension as well as demolition and reconstruction was determined through two different methods i.e. Revit and IStructE guide. Finally, a comparative study was performed to study the carbon impact resulting from the proposed scenarios. The carbon footprint of both scenarios was compared and assessed with the SCORS rating.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

In this study, two scenarios were implemented to assess the environmental benefit of vertical extension. The scenarios refer to vertical expansion with two additional floors (Scenario 1) and demolition and reconstruction (Scenario 2). Since the original design details of the existing structure were not readily available, the design for the existing structure was performed using SCIA Engineer to determine its structural system. The existing building was then introduced with additional two floors. Linear analysis was performed on both building models, and the critical structural elements and support reactions were identified and compared. Besides, the technical challenges associated with vertical extension were explained. The carbon impact of both scenarios was examined and compared. The objectives of this study were accomplished. The key results and findings of this research corresponding to the objectives of this research are outlined as follows:

i. SCIA Engineer analysis were performed for the existing building, and the results revealed that the existing structural elements are able to sustain the additional loads from two extended storeys without the need for structural reinforcement. The critical column was identified at N2609 with the highest support reaction of 15611.1 kN under ULS1. The column remains the most crucial element after introducing two additional storeys.
ii. The model expansion causes the increase in overall support reactions mainly because the structural elements are required to bear a greater self-weight of the building. Under ULS, the difference in support reactions between the existing and extended building models ranges from 0.89 kN to 1078.73 kN, and the percentage difference ranges between 0.18 % to 12%. In contrast, due to increased height, the difference reaction forces of the two models vary from 1.16 kN to 524.28 kN, with a percentage difference ranging from 3.34 % to

46.09 %. Hence, it can be concluded that wind load is one of the most important aspects to be considered while extending the building vertically.

iii. The common technical challenges associated with vertical extension include the availability of the information for the existing building, actual conditions of the building, constructability and installation methods, installation of building services, building retrofitting, fire protection requirements, and accessibility issues. Findings revealed that lightweight structural solutions and pre-fabrication are feasible and suitable for extension projects.

iv. Hawkins\Brown Emissions Reduction Tool (H\B:ERT) in Revit and IStructE guide are helpful in assessing carbon emissions throughout the building's lifecycle. Revit measures the CO_2 emissions from production until the end-of-life stage, whereas IStructE guide only covers the production and construction stage. Both methods show that the production stage of structural materials is the major contributor to CO_2 emissions.

v. Vertical extension is capable of reducing carbon emissions and bring forth environmental benefits as it avoids wasteful demolition and reconstruction processes. The results show that carbon emissions from Scenario 2 (11006.218 tCO_2e) were significantly higher than in Scenario 1 (386.123 tCO_2e). In Scenario 2, the new construction resulted in the highest CO_2 emissions (99 % of the total), accounting for 10891.510 tCO_2e emissions. With reference to the SCORS rating scheme, Scenario 1 obtained a C rating (222.371 $kgCO_2e/m^2$) whereas Scenario 2 has a D rating (281.115 $kgCO_2e/m^2$).

5.2 Recommendations for future work

This research examines opportunities for vertical extension and the resulting carbon impact. The findings obtained are limited by certain boundary constraints. The following are some suggestions for further study:

i. The present study does not include the vertical extensions, which require redesigning and structural interventions. As a result, future research may explore other vertical extensions that require modifications or the addition of the stabilising system to the existing structure and subsequently evaluate the environmental impact of structural alterations.

ii. Since the production of materials contributes to the significant portion of carbon emissions, it is recommended to study further and compare the carbon footprint of the extension corresponding to different material selections.

iii. Future studies could examine the financial viability and profitability of vertical extensions by considering all financial aspects of cost analysis, risk and sensitivity analysis.

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APPENDICES

Appendix A: Tables

Table A-1: Embodied Carbon Factors for Typical Structural Materials During Production Stage (Orr, Gibbons and Arnold, 2020).

Material	Type	Specification/details	A1–A3 ECF ($kgCO_2e/kg$)	Data source
Concrete	*In situ*: piling, substructure, superstructure	Unreinforced, C30/37, UK average ready-mixed concrete EPD[1] (35% cement replacement)	0.103	MPA, 2018[2]
		Unreinforced, C32/40, 25% GGBS cement replacement[3]	0.120	ICE V3[4]
		Unreinforced, C32/40, 50% GGBS cement replacement	0.089	ICE V3
		Unreinforced, C32/40, 75% GGBS cement replacement	0.063	ICE V3
		Unreinforced, C40/50, 25% GGBS cement replacement	0.138	ICE V3
		Unreinforced, C40/50, 50% GGBS cement replacement	0.102	ICE V3
		Unreinforced, C40/50, 75% GGBS cement replacement	0.072	ICE V3
	Precast	Unreinforced, C40/50 with average UK cement mix	0.178	ICE V3
		Reinforced, 150mm prestressed hollow core slab: British Precast Concrete Federation average EPD	50.2kgCO_2e/m^2	BPCF, 2017[5]
Steel	Reinforcement bars	UK: BRC EPD	0.684	BRC, 2019[6]
		Worldwide: Worldsteel LCI study data, 2018, world average	1.99	ICE V3
	PT strands	Assume the same as reinforcement bars		
	Structural sections	UK open sections: British Steel EPD	2.45	BS, 2020[7]
		Europe (excl. UK): Bauforumstahl[8] average EPD	1.13	Bauforumstahl, 2018
		Worldwide: Worldsteel LCI study data, 2018, world average	1.55	ICE V3
	Galvanised profiled sheet (for decking)	UK: TATA Comflor EPD	2.74	TATA, 2018
Blockwork	Precast concrete blocks	Lightweight blocks	0.28	ICE V3
Brick	Single engineering clay brick	Generic, UK	0.213	ICE V3
Timber, excl. carbon sequestration[9], [10]	Manufactured structural timber	CLT, 100% FSC/PEFC	0.437	ICE V3
		Glulam, 100% FSC/PEFC	0.512	ICE V3
	Studwork/framing/flooring	Softwood, 100% FSC/PEFC	0.263	ICE V3
	Formwork	Plywood, 100% FSC/PEFC	0.681	ICE V3
Plasterboard	Partitioning/ceilings	Minimum 60% recycled content	0.39	ICE V2
Intumescent paint	For steelwork	Specific EPD: Amotherm steel WB, Amonn	2.31	AMONN, 2019[11]

Table A-2: Transport Emissions Factors for Various Transportation Modes (Orr, Gibbons and Arnold, 2020).

Mode	TEF_{mode} ($gCO_2e/kg/km$)
Road transport emissions	0.10650
Sea transport emissions	0.01614
Freight flight emissions	0.59943
Rail transport emissions	0.02556

Table A-3: Waste Factors for Different for Typical Structural Materials (Orr, Gibbons and Arnold, 2020).

Material/product	Waste rate (WR)	Waste factor (WF)[1]	WRAP Net Waste Tool reference
Concrete *in situ*	5%	0.053	Table 2, concrete *in situ*
Concrete precast (beams and frames)	1%	0.010	Table 2, concrete precast (large precast elements)
Steel reinforcement	5%	0.053	Appendix 1, frame: *in situ* concrete frame generic; Table 2, ferrous metals
Steel frame	1%	0.010	Appendix 1, frame: steel frame generic
Blockwork	20%	0.250	Table 2, bricks & blocks
Brick	20%	0.250	Table 2, bricks & blocks
Timber frames (beams, columns, braces)	1%	0.010	Appendix 1, frame: timber frame
Timber floors (joists, boards)	10%	0.111	Appendix 1, floor: wooden floor
Plasterboard	22.5%	0.290	Table 2, plasterboard; Table 3: boarding
Sprayed cementitious fire protection	10%	0.111	Table 3: cementitious sprays