SIMULATION OF MODULAR CONSTRUCTION AND COST ANALYSIS FOR THE MARTIAN BUILDING

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

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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

Martian building is a building that build in Mars. In this paper, the focus of the construction method that propose for the Martian building will be the Pre-Fabrication which also called Modular Construction. Modular construction is a modern construction that uses three-dimensional or volumetric units which are prefabricated and are originally fully finished in the factory conditions. After that, assemble on site to form the major parts of buildings or complete buildings. The aim and objective of this paper is to compare the construction method and costing analysis for the Martian building. Simulation of the Modular Construction method under the Martian condition (different gravitational force, pressure, temperature, etc.) using Revit and propose the Modular Construction method for the Martian building with economical costing. The problem statement of this paper is difficulty of construction method and costing analysis on the Martian building due to different conditions of Mars and transportation of the materials. This paper discusses the condition of Mars, design loading and material use for the Martian Buildings. Besides that, discuss the characteristics and techniques of the Modular Construction method, comparison of different construction methods and the impact of Modular Construction method to the environment. Finally, come out with the costing analysis of Modular Construction method adopted for Martian Buildings.

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CHAPTER 1

INTRODUCTION

1.1 General Introduction

What is Martian building? Martian building is a building that build in Mars. Nowadays, there are many concepts of construction method that propose for the Martian building. For example, In-Situ Resource Utilization (ISRU), 3D Printing, Pre-Fabrication, Biosynthesis, Radiation Shielding, Underground Construction, and Inflatable Habitats. In this paper, the focus of the construction method that propose for the Martian building will be the Pre-Fabrication which also called modular construction.

Modular construction has gained prominence across diverse sectors of the construction industry over the past 15 years. Previously, modular construction was exclusively associated with portable or temporary structures. However, contemporary construction practices incorporate prefabricated technology through volumetric units in a wide range of buildings, including supermarkets, offices, hospitals, schools, and high-rise residential structures. This shift is influenced by the off-site construction approach, driven by anticipated economic and sustainability advantages (Ogden & Goodier, n.d.).

Modular construction is a contemporary building method that utilizes pre-manufactured, fully finished three-dimensional or volumetric units. These components are produced in factory conditions and later assembled on-site to create essential building sections or entire structures. The establishment of manufacturing processes and facilities at a designated site yields financial advantages over time. Consequently, effective control and coordination among design professionals and the construction team are crucial to maximize the repeated utilization of these prefabricated elements. Additionally, optimizing processes such as installation, delivery, supply, integrated design, and commissioning is essential for managing the overall investment efficiently (Ogden & Goodier, n.d.).

Typically, modular construction is employed to create buildings with cell-like structures, consisting of units of similar room size designed for convenient transportation. In contrast, partially or fully open-sided modules are crafted to generate more extensive spaces when two or more units are combined. Certain modular components, including mechanical service units, lift and stair units, bathrooms, and prefabricated roofs that often integrate services, are manufactured to serve as integral and high-value parts of the building (Ogden & Goodier, n.d.).

Modular construction relies on quicker and more efficient factory processes as opposed to the slow and unproductive activities typically associated with on-site construction. However, the investment to fix the manufacturing facilities in the infrastructure of factory production and repeatability of output in production is greater. Moreover, the design time and the manufacturing of prefabricated components are extended with more conventional construction methods (Ogden & Goodier, n.d.).

There are some of the advantages in modular construction with time, quality, and cost. For example, shorter build time will reduce the cost of site management and early return of the investment. The pre-delivery checks and factory-based construction process will result in excellent quality. The double-skin nature of the construction will provide fire safety and thermal insulation and excellent acoustic. This means each of the modules is effectively away from its neighbors. Moreover, clients can experience a reduction in design costs as a significant portion of detailed design tasks is handled by the modular supplier. The use of modular units, given their size, contributes to lightweight structures, minimizing waste and material usage. This approach also presents favorable conditions for material recycling during factory production. Enhanced productivity within factory processes allows for decreased on-site labor, given that module installations are carried out by specialized teams. In addition, factory and site activities are safe. Modular construction also provides less disturbance to the adjacent buildings during the construction. Lastly, the building can dismantle and maintain the asset value due to the reuse of the modules (Ogden & Goodier, n.d.).

Modular construction method provides an effective way to construct a complete building by joining all the module units. This can reduce the time of on-site construction and reduce the on-site labor. However, it requires specialist teams for the joining technique in the on-site construction. In this paper is to determine whether this modular construction method suitable to be adopted for the Martian building. So that, the condition of Mars will be taken into consideration.

1.2 Importance of the Study

The important of this study is to simulate the module and propose cost analysis for the Martian building by using Modular Construction method. This study also investigates the comparison of different types of construction method for Martian building with the suitability and costing analysis.

1.3 Problem Statement

There is difficulty of construction method and costing analysis on the Martian building due to different conditions of Mars and transportation of the materials.

1.4 Aim and Objectives

1. To compare the construction method and costing analysis for the Martian building.
2. Simulation of the Modular Construction method under the Martian condition (different gravitational force, pressure, temperature) using Revit.
3. Propose the Modular Construction method for the Martian building with economical costing.

1.5 Scope and Limitation of the Study

There are many types of construction method that propose for Martian building. However, this study is more focused on the simulation of the Modular Construction method and propose costing analysis for the Martian building. The comparison between different types of construction method will be shown in this study.

1.6 Contribution of the Study

The simulation of Modular Construction method and costing analysis for the Martian building can contribute to the future research as a reference. The concept of Martian building is still new and unknown. Therefore, many of the investigation and proposal are important to enhance the possibility of the Martian building to advance our technology and knowledge in the future.

1.7 Outline of the Report

This report is regarding the simulation of Modular Construction method by using Revit software. This report talks about the introduction of Modular Construction method, comparison between different types of construction method that propose for the Martian building, condition of Mars, characteristics, and techniques of Modular Construction method. This study also provides the costing analysis of the Modular Construction method and propose with economical costing.

CHAPTER 2

LITERATURE REVIEW

2.1 Construction Method for Martian Building

There are many construction methods that propose for Martian building. The construction methods and their definition are shown in Table 1.

Table 1: Construction Method and Definition for Martian Building.

Construction Method	**Definition**	**Costing Analysis**
In-situ Resource Utilization (ISRU)	Given the challenges and costs associated with transporting building materials from Earth to Mars, ISRU involves using local resources available on Mars to construct buildings. This could involve using Martian soil (regolith) as a construction material, possibly by compressing it into bricks or using it as a structural element.	Low cost: ISRU has the potential for relatively lower costs because it relies on using Martian resources (e.g., regolith) instead of transporting construction materials from Earth. This method can significantly reduce the expenses associated with material transportation.
3D Printing	3D printing technology has gained attention as a potential construction method for Mars. Robots	Medium cost: 3D printing technology is flexible and efficient, which

	equipped with 3D printers could use local materials to create structures layer by layer. This method is efficient and could adapt to the available resources.	can lead to cost savings. However, the costs may vary depending on the complexity of the equipment and the materials used. Initial setup costs for advanced 3D printers might be relatively high.
Pre-Fabrication	Parts of the building could be manufactured on Earth and transported to Mars. This would require careful planning and design to ensure that the components survive the journey and can be easily assembled on Mars.	Medium to high cost: The cost of pre-fabrication can vary widely based on the complexity and size of the components, the materials used, and the need for specialized transportation. While prefabrication can offer quality control and safety benefits, producing and transporting large, intricate modules can be expensive.
Biosynthesis	Some proposals suggest using biological materials	High cost: Biosynthesis

	or processes to create structures. This could involve using genetically modified organisms to produce building materials or even growing structures using living organisms.	methods may involve genetically modified organisms or bioengineered materials, which can require substantial research and development costs. Additionally, ensuring the reliability and safety of biologically based construction materials might be expensive.
Radiation Shielding	Mars has a thin atmosphere that provides limited protection from cosmic and solar radiation. Building materials themselves could be designed to provide radiation shielding, ensuring the safety and health of future Martian inhabitants.	Medium to high cost: Incorporating radiation shielding into building materials can add to the overall construction costs. The expense depends on the type and amount of shielding required.
Underground Construction	Building structures partially or entirely underground could provide natural protection	Medium cost: Building underground structures on Mars

	against radiation and extreme temperature variations on Mars.	may have relatively moderate construction costs, but excavation and reinforcement of the underground habitats can still be resource intensive.
Inflatable Habitats	Inflatable structures could be transported to Mars in a compact form and then inflated to create habitable spaces. These structures could be covered with regolith for added protection.	Low to medium cost: Inflatable habitats are compact for transportation and installation. While the technology itself is generally cost-effective, ensuring their durability and longevity in the harsh Martian environment may add to the costs.

2.1.1 In-Situ Resource Utilization (ISRU)

In-Situ Resource Utilization (ISRU) for constructing buildings on Mars involves utilizing materials found on the Martian surface. This method encompasses the collection, processing, storage, and application of materials present or generated on celestial bodies, reducing the need to transport resources from Earth. Research indicates that ISRU has the potential to provide crucial materials such as water, rocket propellants, and construction resources. The primary focus of ISRU lies in civil engineering and surface construction, exploring the possible use of Martian soil, basalt, volcanic ash, and Martian concrete as construction materials. Martian soil, comprising construction material aggregates, can be tested on Earth using Martian soil simulants in Mars probe experiments. Basalt, utilized for construction purposes, serves various functions, including as building materials, pavement materials such as concrete and asphalt, cobblestones, and decorative crafts. Volcanic ash, on the other hand, is employed in building materials like pozzolan cement and thermal insulation, as well as in pavement materials like concrete pavement (Liu et al., 2022).

(Liu et al., 2022) states that the predominant atmospheric compositions on Mars and Earth differ significantly. The predominant atmospheric compositions on Mars and Earth differ significantly are shown in Table 2.

Table 2: The predominant atmospheric compositions on Mars and Earth differ significantly (Liu et al., 2022).

Major atmospheric compositions	Mars (%)	Earth (%)
CO_2	95.1	M*
N_2	2.59	78.08
Ar	1.94	M*
O_2	0.16	20.95
CO	0.06	M*

Note: M* means the composition is minor.

Table 2 shows the major atmospheric compositions such as carbon dioxide (CO2), nitrogen (N2), argon (Ar), oxygen (O2) and carbon monoxide (CO), percentage of major atmospheric compositions in Mars and percentage of major atmospheric compositions in Earth (Liu et al., 2022).

Based on the research of (Li et al., 2021), there are few types of the mix proportion of Martian concrete and compressive strength of Martian concrete are shown in Table 3 and Table 4.

Table 3: The mix proportion of Martian concrete (Li et al., 2021).

Type	Sulfur (wt%)	Magnetite (wt%)	Silica sand (wt%)	Microwave power (W)	Heating time (s)
MC-100-900	40	60	-	100	900
MC-1000-50	40	60	-	1000	50
MCS-100-900	40	30	30	100	900
MCS-200-480	40	30	30	200	480
MCS-500-180	40	30	30	500	180
MCS-1000-50	40	30	30	1000	50

Table 3 shows the types of the Martian concrete, percentage of sulphur, percentage of magnetite, percentage of silica sand, heating time and microwave power (Li et al., 2021).

Table 4: Compressive strength of Martian concrete (Li et al., 2021).

Label (−)	Strength on earth, kgf/mm^2 (MPa on earth)	Strength on Mars, kgf/mm^2 (MPa on earth)
MC-100-900	1.29 ± 0.12 (12.63)	3.35 ± 0.31
MC-1000-50	1.17 ± 0.09 (11.46)	3.04 ± 0.23
MCS-100-900	1.78 ± 0.13 (17.41)	4.62 ± 0.34
MCS-200-480	1.22 ± 0.10 (11.91)	3.16 ± 0.26
MCS-500-180	1.66 ± 0.13 (16.30)	4.32 ± 0.34
MCS-1000-50	1.16 ± 0.10 (11.37)	3.02 ± 0.24

Table 4 shows the types of the Martian concrete, the compressive strength of Martian concrete on Earth and the compressive strength of Martian concrete on Mars (Li et al., 2021).

These all the materials should undergo the experiment to investigate the properties of these materials to adopt in the construction of the Martian building because the condition of the Mars is different from Earth. Therefore, these materials act as the important role to deal with the condition of the Mars.

Materials employed in space construction and energy conversion equipment must satisfy three essential criteria: resiliency, durability, and economy (Liu et al., 2022) are listed below:

1. Resiliency: It is expected that building materials will perform well in the harsh environments of Mars, which are marked by low pressure, frigid temperatures, and a variety of environmental factors. For example, building materials must withstand extremes in temperature, including highs and lows, significant temperature changes, and meet the criteria for thermal insulation of humans in the Martian atmosphere. Moreover, one cannot ignore the possibility of meteorite impacts posing a harm. Currently, planetary construction materials and additively made materials are being investigated by NASA's Additive Construction with Mobile Emplacement (ACME) project for their resistance to the impact of hypervelocity.

2. Durability: The materials employed in additive construction must meet specific criteria, including the capability to be accurately deposited in a predictable form, the ability to sustain a layered structure over time, effective bonding with adjacent layers, and sufficient structural integrity for practical applications. Given the challenging climatic conditions, it is crucial to ensure the material's resilience in low-temperature, low-pressure environments and incorporate features that offer protection against intense UV and solar radiation. Employing reflective substances is one strategy to prevent material aging and enhance durability.

3. Economy: The enormous expense of transferring materials from Earth to space serves as the justification for ISRU. Future studies could examine the financial trade-off between bringing necessary materials from Earth for the full life cycle and producing building materials from Martian in-situ resources.

2.1.2 3D Printing

3D Printing is a technology that use the robot equipped with the 3D printer to construct the structure layer by layer. There are many requirements that need to be considered for 3D Printing such as design of the habitat, design of the construction setup and logistics, design of construction sequence - 4D simulation. The design of the habitat includes the parametric problem formulation and parametric optioneering. The design of the construction setup and logistics shows the setup of the printing system on how to simulate the model. The physical experiment of 3D Printing is shown in Figure 1 and the final 3D printed concrete structure is shown in Figure 2 (Muthumanickam et al., n.d.).

Figure 1: (Above) Experimental exploration of diverse edge configurations and material deformation at the edges in the process of robotic 3D printing. (Below) Bead failure on the interior side of a tapering cone (indicated by a dotted yellow line). (Lower right) Cross-sectional representation of the module's geometry at the connector, highlighting fillet edges (Muthumanickam et al., n.d.).

Figure 2: The completed concrete structure produced through 3D printing at the construction site (Muthumanickam et al., n.d.).

Hence, a unified Building Information Modelling (BIM) platform linked to a variety of analysis and simulation tools played a pivotal role not only in designing the habitat on Mars but also in shaping the structure and its associated intricacies. It played a crucial role in orchestrating construction sequences and conducting 4D simulations for the 3D printing of the world's inaugural fully enclosed and tapered concrete building on an architectural scale, accomplished without any additional support structures. This achievement was made possible by the BIM platform's integration of generation, assessment, and optimization functionalities, enabling the identification of optimal solutions for diverse environments such as Earth and Mars. The platform captured the intricate interplay between material properties, printing techniques, and design considerations, facilitating the simultaneous evolution of the shelter's design, the printing system, the printing setup, and the construction process. This approach embodies a comprehensive design methodology. The platform's formulation was substantiated by extensive experimental testing, which revealed the correlations among variables related to material, printing, and design aspects, along with the potential range of values for each variable (Muthumanickam et al., n.d.).

The experimental testing concentrated on distinct aspects of the design, such as determining the optimal printing angle, managing sharp corners, placing windows, ensuring effective sealing, and coordinating the actions between the printing and window placement robots. This testing successfully led to the 3D printing of a scaled-down shelter during a direct comparison. However, the attempt to print the entire shelter encountered obstacles, exposing issues like over extrusion in specific areas, more significant material deformation than anticipated, and variations in the printing toolpath alignment across different printing sessions, among other challenges. These issues had a detrimental impact on the autonomy of the process, prompting the need for further research to address and resolve these challenges (Muthumanickam et al., n.d.).

2.1.3 Inflatable Habitat

An inflatable structure constructed from regolith can be created by utilizing materials such as dry-stacked earth building blocks or connecting them with a binding substance. These materials exhibit brittleness and are effective solely under compressive forces, necessitating the avoidance of tension stress within the structure. The type of the structure include vaults, domes and shell structures are shown in Figure 3 (Mintus, n.d.).

Figure 3: Examples of adobe structures, a) vault, b) dome, c) shell structure (Mintus, n.d.).

The primary demand for the construction system is its autonomy. While the structure should be self-supporting once completed, various stresses may arise during the construction phase. Therefore, it is crucial to carefully plan the construction process to prevent the formation of unstable structures and safeguard against external loads (Mintus, n.d.).

As mentioned earlier, the approach to connect regolith adobe can involve either dry stacking with interlocking features or using a binding agent. Choosing the latter option would require further analysis of the material and increased processing on Mars, resulting in elevated energy consumption and production time. Therefore, for this investigation, the choice was made to implement the interlocking system integrated into the design of the building blocks. An additional advantage of the interlocking system is its ability to allow the entire structure to be recycled, eliminating the necessity for a permanent binder. This assembly technique provides flexibility and streamlines the construction process (Mintus, n.d.).

Constructing structures through the interlocking system requires securing the blocks in place until they autonomously lock into the desired configuration. This can be accomplished using supplementary frames and scaffolds or tension cables. Attaining precise robotic assembly is vital for the entirely automated construction process on Mars. Ensuring the blocks are positioned accurately is critical for the structural integrity and effectiveness of the shell (Mintus, n.d.).

(Mintus, n.d.) states the Conditions defining the limits and states of the structural model and the structural analysis comparison between Earth and Mars are shown in Table 5 and Table 6.

Table 5: Conditions defining the limits and states of the structural model (Mintus, n.d.).

Load Case n°	Name	Type	Unit	Earth Value	Mars Value
1	dead load	uniformly distributed			
2	wind load	uniformly distributed	kN/m²	1	0,625
3	micrometeorites impacts	point load	kN	_	14

Structure	Comment	Unit	Earth Thickness	Mars Thickness
Cross Section	rectangle	cm	100	100
Span		m	8	8

Safety Limits	Type	Comment	Unit	Earth Value	Mars Value
1	compressive stress		MPa	0,6	0,6
2	tensile stress	1/20 - 1/50 of compressive	MPa	0,03	0,03
3	deformation	L/240	m	0,033	0,033

Material	Parameter	Unit	Earth Value	Mars Value
1	Young's Modulus	MPa	100	100
2	Compressive Strength	MPa	0,6	0,6
3	Shear Strength	MPa	40	40
4	Density	kg/m³	1700	1700
5	Tensile Strength	MPa	0,03-0,012	0,03-0,012
6	Specific weight	kN/m³	16,7	6,3

Table 6: Structural analysis comparison between Earth and Mars (Mintus, n.d.).

Parameter	Unit	Safety Limit	Earth Value	Mars Value
Compressive stress	MPa	0,6	0,013	0,0014
Tensile Stress	MPa	0,03	0,003	0,0003
Deformation	m	0,033	0,818	0,17

The material requirements for construction on Earth surpass those for Mars. Consequently, the compressive stress, tensile stress, and deformation experienced on Mars are lower than those on Earth. Different segments of structures undergo compressive stress, signifying a notable influence of reduced gravitational forces on structural behaviour. In contrast to Earth, where maximum compressive stress values are generally minimal, Martian structures exhibit concentration at the model's top. On Mars, factors like wind and micrometeorite impacts exert a more significant effect than the dead load associated with specific weight. The wind load, directed upwards, results in higher tensile strength on the structure's sides compared to the compressive strength induced by gravity. This consideration holds critical importance in the structural design process (Mintus, n.d.).

The structural specifications for this building involve the ability to endure substantial temperature variations, resist harm from radiation or micrometeorites, accommodate the necessary volumes and dimensions for inhabitable spaces, provide thermal and radiation insulation, be non-flammable, and resist decomposition (Mintus, n.d.).

2.1.4 Radiation Shielding

In accordance with the mission outlined for the "Building on Mars" project, following DRA 5.0 guidelines, the crew's journey to Mars is scheduled for 27/08/2037, and their return to Earth is planned for 10/08/2039. This results in a 539-day duration of the crew's stay on the Martian surface, during which they will need protection from space radiation. While the 174 days of transit expose the crew to the deep space radiation environment, it's important to note that safeguarding the crew during transit falls outside the scope of this project (Nihat Mert Ogut, 2017).

To reiterate, there are two forms of radiation present on the Martian surface: solar energetic particles (SEPs) and galactic cosmic rays (GCRs). Primarily, the habitat requires effective shielding against GCRs, which act as a constant presence akin to background noise in space. However, the total ionizing doses from GCRs may fluctuate based on solar activities, with the contribution of GCRs to effective doses peaking during solar minima. SEPs pose a more immediate threat of exposure to ionizing radiation in space. In instances of solar flares and heightened solar activities, the doses to which the crew is exposed can easily surpass career limits, posing risks to their health. Furthermore, depending on the severity of solar activity and flares, these doses may potentially lead to rapid fatalities (Nihat Mert Ogut, 2017).

Multiple shielding methods exist to mitigate the impacts of SEPs and GCRs. While passive shielding is effective in safeguarding the crew from solar energetic particles, its efficacy is constrained when it comes to GCRs. An alternative strategy for protecting against ionizing space radiation involves active shielding. This approach encompasses the utilization of electrostatic fields, plasma shields, as well as confined and unconfined magnetic fields (Nihat Mert Ogut, 2017).

The efficiency of a shielding material can be assessed by examining how the material transports energetic particles within the shield. This evaluation involves analysing the interactions between local environmental particles and the atoms and nuclei of the shielding material. The difficulty lies in identifying materials that possess both the structural strength required for habitat construction and effective shielding properties against ionizing space radiation. Materials with elevated hydrogen content have demonstrated efficacy in shielding against radiation and protecting the crew. The radiation shielding properties of a material are directly linked to its chemical composition and mass density, both of which are critical parameters (Nihat Mert Ogut, 2017).

The objective is to achieve the desired radiation shielding levels by introducing a minimum of 80 g/cm2 of water as a shielding material. Using 50 g/cm2 of water shielding reduces the annual GCR dose equivalent to 0.39 cSv, while employing 100 g/cm2 of water shielding decreases the dose equivalent to 0.33 cSv (Nihat Mert Ogut, 2017).

The shielding envelope consists of materials and thicknesses are listed below:

G4_Al (aluminum): 2.54cm (to mimic the Mars atmosphere)
G4_Polyethelene: 20mm (to mimic 20mm of ETFE)
G4_Water: 800mm (as the main radiation protective shield, that will be formed in ice)
G4_Polyethelene: 20mm (to mimic 20mm of ETFE)
G4_Air: 60 mm (to mimic Aerogel for insulation purposes)

G4_Carbondioxide: 200mm (to mimic the CO_2 bags for insulation purposes)

G4_Mylar: 10 mm (used for insulation purposes)

Given the designed envelope, the annual GCR dose equivalent is anticipated to be nearly as minimal as when employing 100 g/cm2 of water as shielding, resulting in an annual GCR dose equivalent of 0.33 cSv. Nevertheless, it's crucial to acknowledge that the mission duration extends beyond a year, leading to a higher GCR dose equivalent. Additionally, the total dose equivalent will be influenced by the contribution of SEP, necessitating further exploration (Nihat Mert Ogut, 2017).

2.2 Martian Building

Martian building is a building that constructed at the Mars. When come to the design of the Martian building, the design loading and the material use should take into consideration.

2.2.1 Design Loading

As we know that the gravitational force of Earth and Mars are different so the design of the loading will be different. When it comes to the design of the building, we need to consider the load combination which means the loading that applied to the structure. Normally the load combination that applied on the Earth are differentiated into a few types such as dead load, live load, wind load, snow load and earthquake load. As the Eurocode EN 1990 state that the design loading in ultimate limit state, design load = 1.35Gk + 1.5Qk. Gk is the dead load and Qk is the live load. Dead load is the permanent load like the unit weight of the structure, unit weight of the material which is the fixed loading and live load is the variable load like furniture, capacity of the people which the loading is not fixed (Soureshjani et al., 2023) (Soureshjani & Massumi 2022).

The assessment of structural stability, geometric compatibility, and short-term and long-term adequacy involves employing effective analysis methods under dynamic and static structural loads. Structural loads typically fall into environmental and axial categories. Given the unique conditions on Mars, structural loads are classified into three types: lateral, vertical, and special. These load data are gathered using Martian landers, orbiters, and rovers, considering the specific conditions on Mars. Vertical loads encompass rain, snow, and gravity loads. The gravity load, a crucial consideration in structural design, is based on the planet's gravitational acceleration. This gravity load is further categorized into dead load and live load. Notably, Mars has a lower gravitational acceleration (3.71 m/s^2) compared to Earth (9.81 m/s^2). Subsequently, this gravitational acceleration is applied to determine the design loading for dead and live loads. Lateral loads involve wind and marsquake loads, while special loads encompass internal pressure, asteroid impact, meteoroid and micrometeoroid impact, dust accumulation, and thermal stress (Soureshjani et al., 2023) (Soureshjani & Massumi 2022).

Table 7: Mapping the loads on residential structures on Mars (Soureshjani et al., 2023).

Structural load	Category	Amount	Units	Section	Symbol
Rain load	Vertical loads	0	–	2.1.1	R_M
Snow load	Vertical loads	0	–	2.1.2	S_M
Dead load	Vertical load	$D_M = mg_M$	N	2.1.3.1	D_M
Live load	Vertical load	≈ 200 kg/m^2 (742 N/m^2) + effect of instruments and equipment†	N	2.1.3.2	L_M
Wind load	Lateral load	$7.5H_{mf}A$ ††	N	2.2.1	W_M
Marsquake load	Lateral load	≈ 0	–	2.2.2	E_M
Internal pressure	Special load	101,325	Pa	2.3.1	I_P
Asteroids impact	Special load	Negligible	–	2.3.2	A_I
Meteoroids and micro-meteoroids impact	Special load	Negligible	–	2.3.3	MI_M
Dust accumulation	Special load	Negligible	–	2.3.4	DA_M
Thermal stress	Special load	The effect of thermal stress should be calculated based on the thermal expansion coefficient (α), Young's modulus (E), temperature change (ΔT) and geometry of structure	Pa	2.3.5	T_M

Table 7 shows mapping the loads on residential structures on Mars which consists of structural load, amount of the loading, the units of the loading and the symbol of the loading. As we can see from the Table 7, the rain load and snow load are 0. The dead load, live load, wind load and internal pressure are calculated. The marsquake load is approximately 0 so can ignore. The asteroids impact, meteoroids and micrometeoroids impact and dust accumulation are negligible because they will not affect the design of the structure. Thermal stress will be calculated based on the coefficient of thermal expansion (α), Young’s modulus (E), change of temperature (ΔT) and structure geometry (Soureshjani et al., 2023).

Design loading plays an important role in the design of the structure. Due to the different condition of the planet, the number of structural loads that we consider are different between Earth and Mars. The above data is a valuable contribution to the design of the structure so the design of the structure will be more easily, and the costing of the design is easy to control. If the condition of the planet is unknown, it is difficult to design the loading maybe will consider all the factors and the costing of the design will be higher.

2.2.2 Material

The main material that is used to construct a building is concrete. The volume of the construction will affect the energy consumption which means less concrete used for construction can reduce the energy required. The less volume of concrete required can reduce the cost and the time of construction. The material that the Martian uses should depend on the condition of Mars. The Mars condition can be based on the Martian surface environment and Martian soil. The Martian surface environment means the gravitational acceleration of Mars which is 3.71 m/s^2, rotation period which is 1.026 earth days and the temperature of Mars which is 20^oC during the day and -140^oC at night. Martian soil is studied based on the thermal, optical, and mechanical properties of the soil. There are many substances to be found on the Martian soil such as sulfur, calcium, suspected magnesium carbonate, amorphous silica and glassy material or impact glass (Soureshjani & Massumi 2022) (Hu et al., 2022).

There are some types of concrete that applied to Mars depending on the preparation method of the concrete, mechanical properties of the concrete and concrete durability. Preparation method is a process on how to generate concrete based on the mixing material, temperature control, different kinds of process, etc. Mechanical properties mean the properties of the material used, characteristic of the concrete, etc. Concrete durability means the life span of the concrete, can the concrete withstand the loading, will the environment affect the concrete to make it fail, etc. (Soureshjani & Massumi 2022) (Hu et al., 2022).

Table 8: Comparison between different concretes (Hu et al., 2022).

Concrete categories	Material composition	Applicable area	Compressive strength	Durability	Characteristics
Calcium Aluminate Concrete (by DMSI)	Calcium Aluminate Cement + Water + Aggregate	Lunar	69–120 MPa	Vacuum and low temperature environment have little effect on it.	Fast hydration of cement; Can save 50% cement; Large water demand; High energy consumption for material preparation; Only for prefabricated parts High compressive strength.
Sulfur Concrete	Sulfur + Aggregate	Lunar & Mars	33.8–54 MPa	Poor durability under vacuum, high temperature, and temperature cycling conditions.	No water needed; High early compressive strength.
Magnesia Silica Concrete	MgO + amorphous silica + Water + Aggregate	Mars	18–87 MPa		Large water demand; The superplasticizer cannot be produced on-site; Low energy consumption for material preparation; High compressive strength; The method of obtaining active SiO_2 is unknown.
Polymer Concrete	Polymer + Aggregate	Lunar	12.6–71 MPa		No water needed; Light weight; High tensile strength; Good radiation shielding ability Polymers cannot be produced on-site
Geopolymer Concrete	Geopolymer + alkali activator + Water + Aggregate	Lunar	26.7–45 MPa	Good durability under temperature cycling and vacuum conditions.	Alkali stimulator cannot be produced on-site; Low water requirement

Table 8 shows the comparison between different concretes based on the material composition of concrete, applicable area, compressive strength of concrete, durability of the concrete and characteristics of the concrete. Sulfur concrete and magnesia silica concrete are applied at Mars. Sulfur concrete is produced by mixing sulfur and aggregate. This kind of concrete gives 33.8-54 MPa of compressive strength. Sulfur concrete will produce poor durability when it is temperature cycling conditions, high temperature and vacuum. During the mixing process, no water is needed for this concrete, and it will provide high early compressive strength. Magnesia Silica Concrete is produced by mixing magnesium oxide (MgO), amorphous silica, water, and aggregate. This kind of concrete gives 18-87 MPa of compressive strength. Magnesia Silica Concrete needs large water demand and the superplasticizer cannot be produced on-site. The consumption of energy is low during the material preparation. This concrete will give high compressive strength. However, the way to obtain active SiO_2 is unknown (Hu et al., 2022). Different kinds of concrete will give different results and characteristics. Therefore, selection of concrete is very important to provide a good structure that will not easily fail and is highly durable. Table 8 shows a clear picture of the characteristics of the concrete so the selection of concrete that is used for the construction can be more effective.

2.3 Characteristics and Techniques

Modular construction is also known as PPVC (Prefabricated Prefinished Volumetric Construction). Modular construction is a modern construction method that is applied in many countries nowadays. There are many countries apply modular construction method in high-rise buildings such as Australia, China, Singapore, UK, and US (Thai et al., 2020).

Table 9: A list of the ten tallest modular buildings globally (Thai et al., 2020).

No.	Project	Storey	Year	Location	Modular type	Material	Highlight
1	Collins House	60	2019	Melbourne, Australia	2D panel and 3D volume	Concrete	The tallest building combined both penalised and volumetric methods
2	J57 Mini Sky City tower	57	2015	Changsha, China	2D panel	Steel	The fastest built buildings upon completion (in 19 days)
3	Croydon Tower	44	2020	London, UK	3D volume	Steel	The tallest volumetric modular building upon completion
4	Atira Student Accommodation	44	2018	Melbourne, Australia	2D panel and 3D volume	Concrete	Combining both penalised and volumetric methods
5	La Trobe Tower	44	2016	Melbourne, Australia	2D panel and 3D volume	Concrete	Combining both penalised and volumetric methods
6	Clement Canopy	40	2019	Singapore	3D volume	Concrete	The tallest volumetric modular building
7	B2 Tower	32	2016	New York, USA	3D volume	Steel	The tallest volumetric modular building upon completion
8	T30 Tower	30	2011	Xiangyin, China	2D panel	Steel	The fastest built buildings upon completion (in 15 days)
9	Apex House	29	2017	London, UK	3D volume	Steel	The tallest volumetric modular building in Europe
10	SOHO Tower	29	2014	Darwin, Australia	3D volume	Steel	The tallest volumetric modular building upon completion

Table 9 shows a list of the ten tallest modular buildings globally. It shows the name of the project, number of stories of the building, constructed year, project location, modular type for project construction, material used in the project and the highlights of the project (Thai et al., 2020).

There are two primary structural systems employed in the construction of modular high-rise buildings: 2D panelized systems and 3D volumetric systems. These systems encompass module dimensions, types, and lateral stability components. The 2D panelized system typically requires more on-site assembly, while the 3D volumetric system leans towards more off-site prefinishing (Thai et al., 2020). Additionally, a modular framing system is utilized for certain modules, involving the incorporation of bracings to assess the viability of adopting a modular braced frame within the overall modular structure. This modular framing system can be categorized into unbraced modular frame systems, steel-braced modular frames, and those incorporating a reinforced concrete braced core (Chua et al., 2020).

Steel Prefabricated Prefinished Volumetric Construction (PPVC) systems are typically utilized in commercial and institutional structures, where open space is a crucial consideration. Conversely, concrete PPVC systems find common application in residential buildings due to their ease of inspection and high durability. High-rise modular construction presents certain challenges, including restrictions on module size and weight imposed by transportation and lifting capacities. Joint design plays a pivotal role in ensuring the robustness and continuity of structural modules with the ability to manage excessive load paths. Since modules are prefabricated off-site and assembled on-site, meticulous attention to the manufacturing and construction processes is essential to prevent cumulative errors during module integration (Liew, 2020). Nevertheless, there are strategies to enhance the efficiency of modular construction, including the use of lightweight modules, long-span modular units, rapid installation joining techniques, the adoption of composite design, consideration of factors such as lateral stability and robustness in modular high-rise building design, and adherence to fire safety requirements (Liew 2020) (Liew et al., 2019).

The joining techniques of modular construction are very important because the unsuitable joining techniques will lead the structure to fail. There are some of the joining techniques. Firstly, external plate connection that shows in Figure 4. External plate connection can be easily done on-site during module assembly, it does not require any module access holes, low fire protection cost and low trades number. However, the water penetration is a big issue, high cost in maintenance and inspection, danger working environment and the inflexibility of the architectural (Dai et al., n.d.) (Thai et al., 2020).

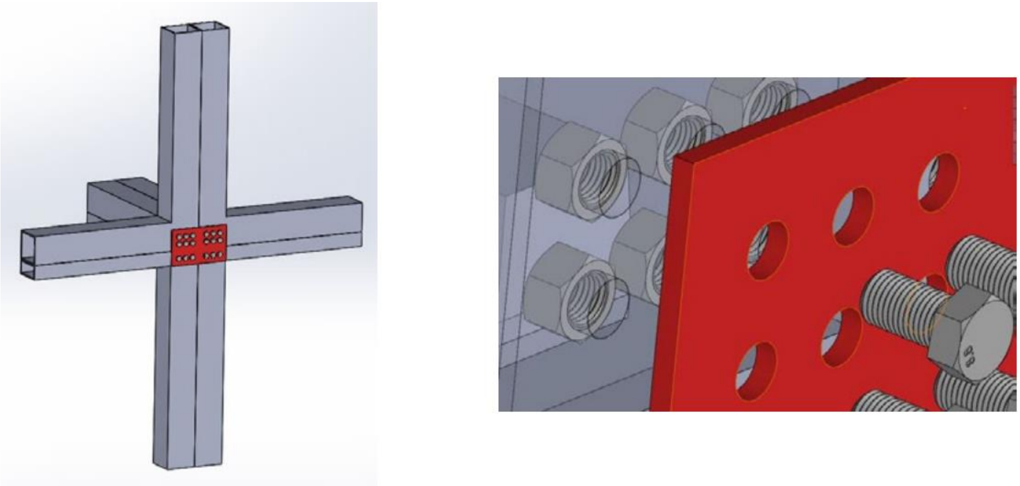

Figure 4: Attachment of an external plate involving nuts that are pre-welded to the inner surface of the column (Dai et al., n.d.).

Moreover, long bolts connection at the beam end is shown in Figure 5. Long bolts connection at the beam end is easy to be adopted during module assembly, the inspection access is easy to conduct, low fire protection cost, provide safer working environment, low trades number and flexible of the architectural. However, the water penetration is a big issue, and it requires module access holes (Dai et al., n.d.) (Thai et al., 2020).

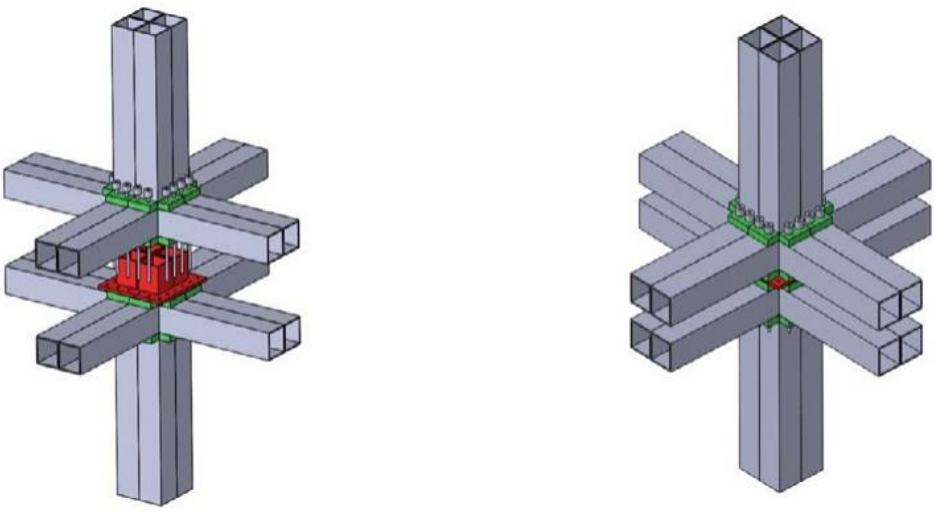

Figure 5: Long bolts connection on the beam with gusset plate and insert sleeves (Dai et al., n.d.).

Furthermore, vertical reinforcements connection is shown in Figure 6. Vertical reinforcements connection provides a good resistance to water penetration, it does not require any module access holes, low fire protection cost and architectural flexibility. However, it is difficult to operate during module assembly, danger working environment, high trades number and the inspection access cannot be made when the modules have been installed (Dai et al., n.d.) (Thai et al., 2020).

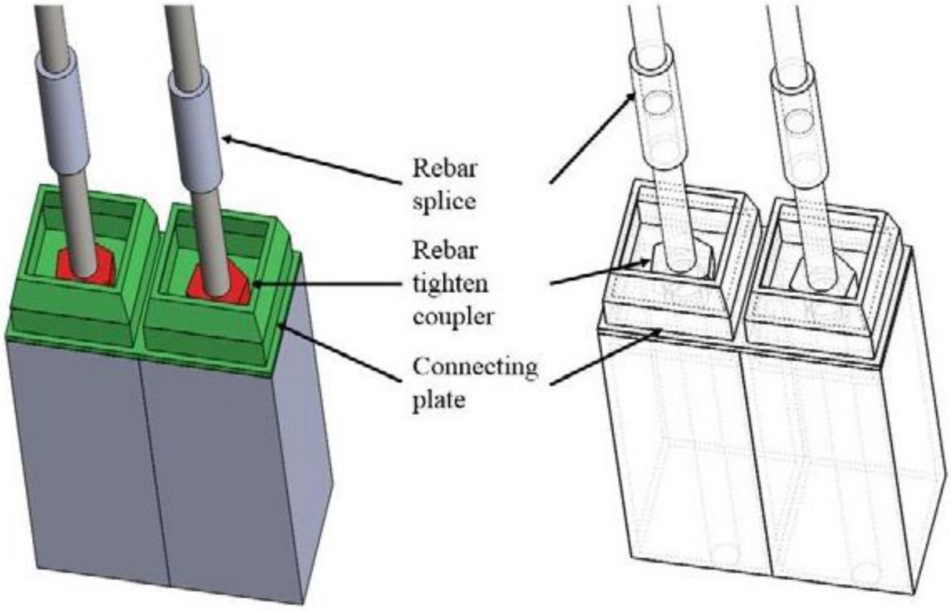

Figure 6: Modified PTMS Joining Technique (Dai et al., n.d.).

Modular construction method can apply at high-rise building and residential. Modular construction method provides lightweight and durable modular units, smart and fast joining techniques and good fire safety of modular buildings. Modular construction should enhance these in the future to provide better performance. This method is a valuable contribution to the construction field which can reduce the construction time on-site.

2.4 Comparison and Case Study

Modular construction method is a modern construction method. It has a different life cycle of building construction than conventional construction method (Kamali et al., 2019).

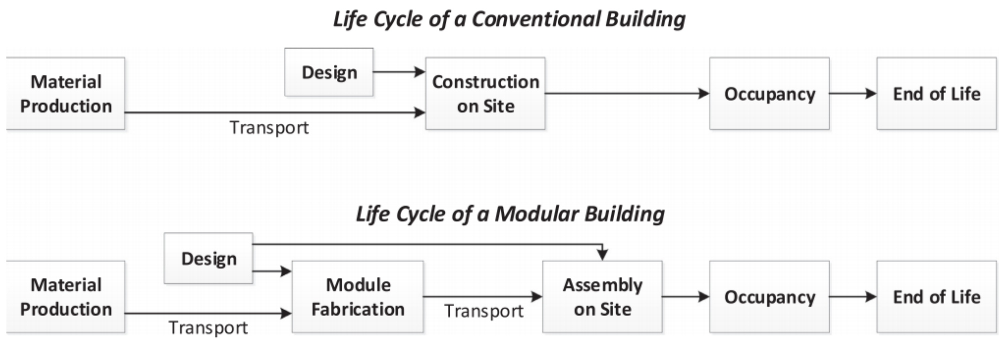

Figure 7: Life cycle of modular versus conventional buildings (Kamali et al., 2019).

Figure 7 shows the different life cycle of modular and conventional buildings. The first step between these two methods is material production then transport for further purposes. In conventional method, material produced will be directly send to the construction on-site for the design of the structure. On other hand, modular construction method will send the produced material for design of module fabrication and then send for assembly on-site. After the construction process, two methods are proceeded to same processes which are occupancy and end of life (Kamali et al., 2019).

Data analysis is required during both the material production and construction phases when comparing conventional and modular construction methods. Material production activities encompass processes like material extraction, processing, and transportation. In the construction phase, activities include construction and installation, as well as the transportation of products and workers (Kamali et al., 2019).

Table 10: Required data for inventory analysis (Kamali et al., 2019).

Construction method	Activity category	Data variable
Conventional and modular	A1, A2	Materials and products (types, quantities)
Conventional	A3	On-site energy (machinery, heating, cooling)
Conventional	A4	Worker transport (number, workdays, commute modes)
		Material/product transport (supplier-site distances, transport modes)
Modular	A3	Off-site energy (machinery in factory, heating, cooling)
		On-site energy (machinery for site work, heating, cooling)
Modular	A4	Worker transport to factory (number, workdays, commute modes)
		Worker transport to site (number, workdays, commute modes
		Material/product transport to factory (supplier-factory distances, transport modes)
		Module transport (factory-site distance, transportation mode)

Table 10 presents the necessary data for inventory analysis, outlining activities denoted as A1, A2, A3, and A4, which correspond to material extraction and processing, material transportation, construction and installation, product and worker transportation, respectively. Variances exist between conventional and modular construction methods, particularly in activities A3 and A4. In the conventional method, A3 encompasses all on-site activities such as finishing, roofing, flooring, structure, and foundation. In contrast, A3 in modular construction involves off-site activities like module fabrication and on-site tasks such as foundation and module assembly. Similarly, A4 in the conventional method involves delivering products and materials to the site, along with the count of on-site workers. On the other hand, A4 in modular construction entails delivering completed modules to the site and employing professional workers for module joining purposes (Kamali et al., 2019).

2.4.1 PPVC and IBS 2D in Malaysia

This study involves comparing the construction time and cost between Prefabricated Prefinished Volumetric Construction (PPVC) and Industrialized Building System 2D (IBS 2D) in Malaysia. IBS 2D refers to the conventional Industrialized Building System 2D method, while PPVC is synonymous with the modular construction method. The comparison encompasses one project for PPVC and 37 for IBS 2D. The number of classrooms varies, with 35 units for PPVC and a range of 24 to 35 units for IBS 2D. The completion years for the respective projects are 2021 for PPVC and 2018 for IBS 2D. PPVC projects are in Putrajaya, while IBS 2D projects are spread across Peninsular Malaysia and the Federal Territory of Labuan (Tambichik et al., 2022).

Table 11: The duration of construction for both the PPVC and IBS 2D methods (Tambichik et al., 2022).

Construction method	Project Location	Number of classrooms (Unit)	Expected Completion (Days)	Actual Completion (Days)
PPVC	Federal Territory of Putrajaya	35	49	56
IBS 2D	Jeli, Kelantan	33	91	91
IBS 2D	Langkawi/ Kota Setar, Kedah	35	91	86

Table 11 shows the duration of construction for both the PPVC and IBS 2D methods. The number of classrooms in two construction methods is around 33 to 35 units. The expected completion of the construction in PPVC method is 49 days whereas IBS 2D method is 91 days. This means the PPVC method requires less time of construction compared to IBS 2D method. The actual completion of construction in PPVC method is 56 days where IBS 2D method is around 86 to 91 days. The IBS 2D method is consistent because the expected completion and actual completion of the construction days are almost the same. Whereas the PPVC method is not consistentt because the actual completion days are more than the expected completion days around 7 days. Although the PPVC method is not consistent, it provides a faster construction time compared to IBS 2D method (Tambichik et al., 2022).

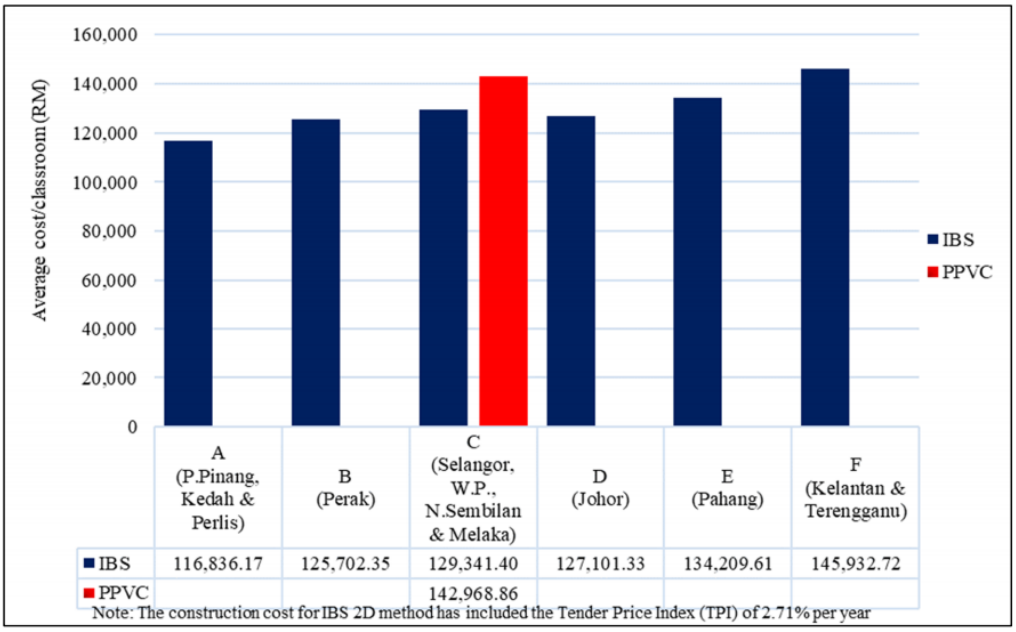

Figure 8: Analyzing the average cost per classroom between PPVC and IBS 2D in various zones (Tambichik et al., 2022).

Figure 8 shows analyzing the average cost per classroom between in various zones. The average cost per classroom of IBS 2D at different zones are RM 116,836.17 at Pulau Pinang, Kedah and Perlis, RM 125,702.35 at Perak, RM 127,101.33 at Johor, RM 134,209.61 at Pahang, RM 145,932.72 at Kelantan, and Terengganu. The zones that applied PPVC method and IBS 2D method are Selangor, Wilayah Persekutuan, Negeri Sembilan and Melaka. The average cost per classroom for PPVC and IBS 2D at these zones are RM 142,968.86 and RM 129,341.40 respectively. PPVC method requires more cost than the IBS 2D because it requires module fabrication in the factory and professional worker for the joining technique of module assembly on-site. Although the cost consumption for PPVC is higher than IBS 2D, the time consumption for PPVC in construction is lesser than IBS 2D (Tambichik et al., 2022).

2.4.2 IPS and PPVC in Singaporean

This project consists of 10 blocks of a 16-storey residential building and 6 story height car parks. The location of this project is East part of Singapore with the name Sengkang Neighbourhood area. The Housing Development Board (HDB) is the developer of this project. IPS is Individual Panel System and PPVC is Prefabricated Prefinished Volumetric Construction. This case study is about the comparison between IPS and PPVC precast system. The benefit of PPVC system over IPS system is the manpower saving (Hossain, n.d.) (Rahman & Rahman Sobuz 2018).

Table 12: Analyzing and comparing the workforce needs (Hossain, n.d.) (Rahman & Rahman Sobuz 2018).

Trade	**Precast system**	**Manpower saving**
Structural (project level)	IPS	10%
	PPVC	40%
Architectural (Trade level)	IPS	30%
	PPVC	70%
MEP (Trade level)	IPS	30%
	PPVC	65%

Table 12 shows the comparison of manpower requirement for structural, architectural and MEP. The manpower saving of PPVC in structural is 40% where IPS only 10%. The manpower saving of PPVC in architectural is 70% where IPS only 30% and the manpower saving of PPVC in MEP is 65% where IPS only 30%. As a conclusion, the manpower saving of PPVC system is higher than IPS system at all levels (Hossain, n.d.) (Rahman & Rahman Sobuz 2018).

Besides that, the casting cycle like slab casting cycle of 12 to 14 days can be decreased to 6 days by using PPVC system, it is very efficient and time saving. Other than that, the quality of workmanship also needs to be studied. PPVC system does not require on-site plaster like skim coat, but it implements a very high quality of finishing than IPS system. Moreover, the building construction cost of IPS system can reduce 20% but PPVC system can reduce 40%. In addition, the form work requirement, scaffolding requirement, and wet concrete requirement can be saved 75%, 75% to 90% and 90% respectively by using IPS system. However, the PPVC system can save 95% for all these requirements (Hossain, n.d.) (Rahman & Rahman Sobuz 2018).

2.4.3 Case Study of PPVC

This case study revolves around the implementation of the Prefabricated Prefinished Volumetric Construction (PPVC) method for the construction of two 40-storey residential blocks in Singapore known as The Clement Canopy. Upon completion, The Clement Canopy held the distinction of being the world's tallest building constructed using the PPVC system. The view of the completed project is shown in Figure 9 (Seng et al., 2021).

Figure 9: View of the completed project (Seng et al., 2021).

The design codes of this project are using European Codes. Other than that, there are many structural systems need to be considered in the project such as the PPVC system modularization, PPVC concrete carcass, PPVC module connection, tower lateral load performance, tower robustness and durability and fire resistance (Seng et al., 2021).

Prefabricated Prefinished Volumetric Construction (PPVC) method means the module is manufactured in the precast factory and then send to the construction site for installation. Firstly, PPVC concrete carcass fabrication is the module manufactured in the precast factory. There are activities that need to be checked at the precast factory such as accuracy of module dimensions, levels and verticality, steel mould dimensions, stability and rigidity and M&E services. After that, PPVC fit-out works like M&E fit-out works, architecture finishing, ponding test and waterproofing works. Lastly, the module can be sent to the site for installation. PPVC system achieves the buildable design, constructability score and manpower productivity. However, there are some challenges in this project such as mindset changing and close collaboration, early contractor involvement, early plan layout design, module size constraint, heavy-duty tower crane lifting, module weight constraint and fitting-out factory space (Seng et al., 2021).

The comparison between PPVC system and other systems shows that PPVC system provides an efficiency of the time consumption in the construction. As the saying goes time is money so the time consumption in the construction is reduced means that cost also reduced. Other than that, the manpower of PPVC system is a big advantage because the manpower of PPVC is saved means that the cost of the construction also reduced.

2.5 Environment

Traditional construction methods are durable, strong, and cost-effective. However, it has some problems such as long construction period, bad construction environment, many constructions waste and environmental pollution. The main reason for environmental pollution is the release of carbon. The material saving of Prefabricated Prefinished Volumetric Construction (PPVC), or modular construction can reduce carbon. There are many ways to reduce the carbon in PPVC system. For example, member structure, industrial production process, demolition construction process and operation stage of modular building, modular building assembly (Wu et al., 2021).

Less concrete used for member structure can reduce the carbon because cement has a large carbon footprint. Cement is one of the materials to produce concrete. Industrial production process such as the module manufactured in the factory with professional equipment and some processes to ensure the quality of the module. This also can save the material used. Modular building assembly prevent many outside constructions, it can reduce the impact on the environment, save time, reduce manpower and improve the safety. This also can provide a green construction site. The transportation equipment should use renewable energy. Demolition construction process can reduce the carbon by reusing the module. Operation stage of modular building such as building technology with modular green nearly zero energy consumption. The building can be designed based on the Standard for Nearly Zero Energy Consumption Buildings. This can produce modules with low carbon building functions. Other than that, passive solar building technology can apply in the module. The passive solar cover can be the window, concrete wall, and floor (Wu et al., 2021).

During construction time, waste generation is always there, and this will affect the environment. Conventional construction methods and modular construction methods will lead to waste generation, which kind of the method will give the least waste generation that can reduce the impact on the environment (Loizou et al., 2021).

Table 13: Evaluating the difference in waste production between traditional and modular construction for Case A and Case B (Loizou et al., 2021).

Structure Element	Case A			Case B		
	Conventional Waste (kg)	Modular Waste (kg)	% Change	Conventional Waste (kg)	Modular Waste (kg)	% Change
Foundation	161	82	−49.1	11,439	2622	−77.1
Flooring structure (plus chassis for modular)	1712	245	−85.7	38,994	1852	−95.3
External walls	1445	233	−83.9	21,783	1822	−91.6
Columns	N/A	N/A	N/A	10,838	96	−99.1
Internal walls	232	70	−69.8	29,795	19,153	−35.7
Beam system	N/A	N/A	N/A	8211	232	−97.17
Stairs	N/A	N/A	N/A	6520	-	−100
Roof	248	82	−66.9	30,049	627	−97.9
Sum	3798	712	−81.3	157,629	26,404	−83.2

Table 13 shows evaluating the difference in waste production between traditional and modular construction for Case A and Case B. Case A show a single-story granny flat in Australia with 63 m^2 gross floor area. Case B show a three-story public school in Australia with 2220 m^2 gross floor area. The structure elements for waste generation are foundation, flooring, columns, external walls, internal walls, beam, stairs, and roof. In Case A, there is no waste generation for columns, beam, and stairs. However, the remaining structure elements are waste, and the Table 13 shows that modular waste consists of 712 kg of total waste whereas conventional waste consists of 3798 kg of total waste which is around 5 times more than the modular waste. In Case B, all the unwanted structure elements become waste, only stairs in modular construction have no waste generation. The total waste of modular waste is 26,404 kg whereas the total waste of conventional waste is 157,629 kg which is around 6 times more than the modular waste. Therefore, modular construction provides less waste generation compared to conventional construction (Loizou et al., 2021).

Construction is always a big issue that has a bad impact on the environment. Therefore, modern construction methods such as modular construction methods can reduce the impact on the environment. Modular construction method is better than the conventional construction method because it provides less waste generation compared to conventional construction method. Therefore, environmental pollution can be reduced.

2.6 Summary

There are many concepts of construction method that propose for the Martian building. For example, In-Situ Resource Utilization (ISRU), 3D Printing, Pre-Fabrication, Biosynthesis, Radiation Shielding, Underground Construction, and Inflatable Habitats. Modular construction method provides an effective way to construct a complete building by joining all the module units. This can reduce the time of on-site construction and reduce the on-site labor. However, it requires specialist teams for the joining technique in the on-site construction.

Design loading plays an important role in the design of the structure. Due to the different condition of the planet, the number of structural loads that we consider are different between Earth and Mars. The above data is a valuable contribution to the design of the structure so the design of the structure will be more easily, and the costing of the design is easy to control. If the condition of the planet is unknown, it is difficult to design the loading maybe will consider all the factors and the costing of the design will be higher. Different kinds of concrete will give different results and characteristics. Therefore, selection of concrete is very important to provide a good structure that will not easily fail and is highly durable. Modular construction method can apply at high-rise building and residential. Although modular construction method provides lightweight and durable modular units, smart and fast joining techniques and good fire safety of modular buildings. Modular construction should enhance these in the future to provide better performance. This method is a valuable contribution to the construction field which can reduce the construction time on-site. The comparison between modular construction system and other systems shows that modular construction system provides an efficiency of the time consumption in the construction. It is always said that time is money so the time consumption in the construction is reduced means that cost also reduced. Other than that, the manpower of modular construction system also a big advantage because the manpower of modular construction is saved means that the cost of the construction also reduced. Construction is always a big issue that has a bad impact on the environment. Therefore, modern construction methods like modular construction methods can reduce the impact on the environment. Modular construction method is better than the conventional construction method because it provides less waste generation compared to conventional construction method. Therefore, environmental pollution can be reduced.

CHAPTER 3

RESEARCH METHODOLOGY

Many of the journals are found on the Google Scholar and UTAR library. Other than journals, much of the information can be found on Google through the website. Much of the information is searched in the keywords of 'Modular Construction' and 'Martian Buildings' that will bring you to the relevant information. Writing of literature review of journals based on the condition of the Martian Buildings, joining technique of Modular Construction method, comparison and case study of the construction method, impact of the Modular Construction method to the environment. Simulation of Modular Construction method under the Martian condition using Revit. The Martian condition includes the gravitational force, pressure, temperature, etc. of Mars. Costing analysis for the Martian Buildings with cost estimation. The costing analysis such as cost of materials, cost of manufacturing, cost of transportation, etc. Lastly, writing of discussion based on the simulation module and costing analysis of the Martian Buildings. These are shown in Figure 10.

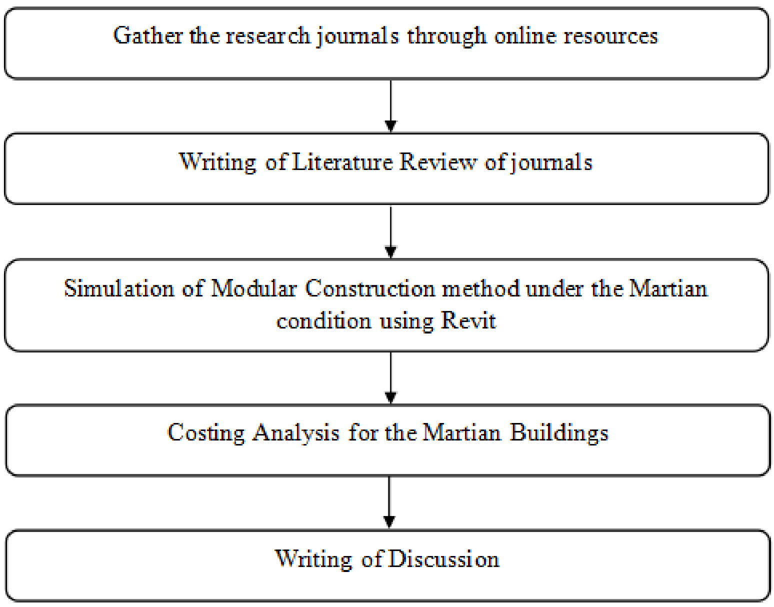

Figure 10: Flowchart of Work Carried Out in the Research.

Revit is a Building Information Modeling (BIM) software designed to assist engineering, architecture, and construction teams in the creation of high-quality buildings and infrastructure. It enables the modeling of shapes, structures, and systems in three dimensions with parametric accuracy, precision, and simplicity. The software is effective in expediting documentation tasks by facilitating instantaneous revisions to plans, elevations, schedules, and sections in response to project changes. Additionally, Revit empowers multidisciplinary teams by providing specialized toolsets within a unified project environment.

Modular construction also known as Industrialized Building System (IBS). Revit is a BIM software to create the model. Manually to draw the model in Revit is a way for modular construction. On other hand, there are many components that provided by myBIM Library of Industrialized Building System to download and use in Revit. The components in myBIM Library of Industrialized Building System can categorize into different categories such as blockwork system, innovative system, metal framework, precast, reusable formwork and timber framework. The myBIM Library can refer to this website (https://www.mybimlibrary.my/product/listing/group/15)

In this paper, the simulation model categorises into 2 options which are container building and precast building. The container building is created by using the "Modular Construction (Container/House)" component as shown in Figure 11. The precast building is created by using the "column", "slab", "beam" and "wall" components as shown in Figure 12.

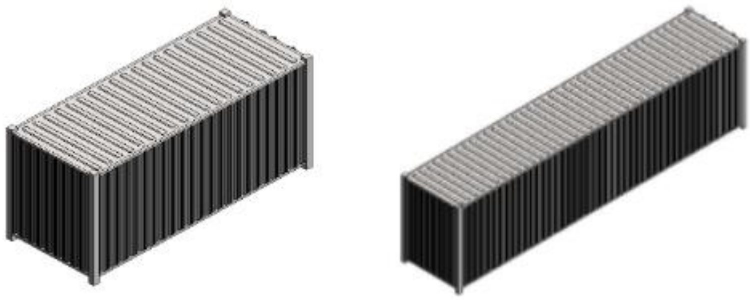

Figure 11: (Left) Container 20 ft, (Right) Container 40 ft.

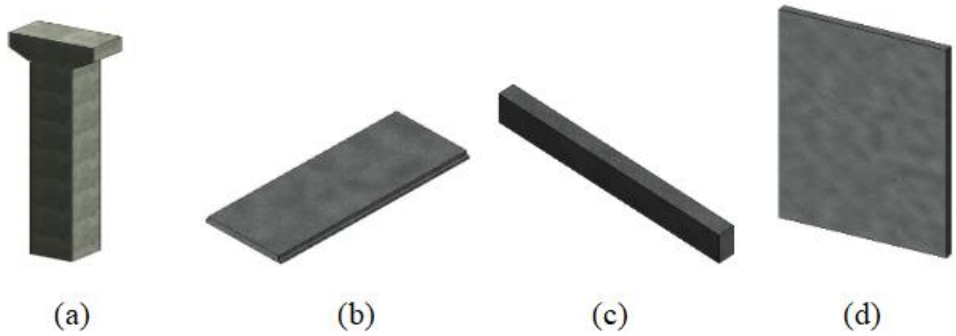

Figure 12: (a) Square column, (b) Slab, (c) Rectangular beam, (d) Wall.

There are some variables should be identified in this paper:

- **Independent Variable:** Different Martian condition such as gravitational force, pressure, temperature, etc.
- **Dependent Variable:** Design of the structures and costing analysis.
- **Control Variable:** Modular Construction method.

The Expected Work Schedule / Timeline

Table 14: The Expected Work Schedule / Timeline.

<table>
<tr><th>Month</th><th>May</th><th>Jun</th><th>Jul</th><th>Aug</th><th>Sep</th><th>Oct</th><th>Nov</th><th>Dec</th></tr>
<tr><td>Gather the research journals through online resources</td><td style="background:yellow"></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Writing of Literature Review of journals</td><td style="background:yellow"></td><td style="background:yellow"></td><td style="background:yellow"></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Simulation of Modular Construction method under the Martian condition using Revit</td><td></td><td></td><td></td><td style="background:yellow"></td><td style="background:yellow"></td><td style="background:yellow"></td><td></td><td></td></tr>
<tr><td>Costing Analysis for the Martian Buildings</td><td></td><td></td><td></td><td></td><td></td><td></td><td style="background:yellow"></td><td></td></tr>
<tr><td>Writing of Discussion</td><td></td><td></td><td></td><td></td><td></td><td></td><td style="background:yellow"></td><td style="background:yellow"></td></tr>
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The Expected Research / Project Outcome or Contribution

The expected project outcome or contribution is the modular construction method able to be adopted in Martian building with economical costing.

CHAPTER 4

RESULTS AND DISCUSSION

The process of modular construction for Martian building are:

1. Prefabricated in factory (include design of structure)
2. Transportation of modular structures to Mars
3. Assembly modular structures in Mars

To design the structure of the building, there are some of the properties that need to take into consideration like the condition of the planet and environmental properties. The condition and properties comparison between Earth and Mars are shown in Table 15.

Table 15: The condition and properties comparison between Earth and Mars.

Properties	Earth	Mars
Dead load, D = mg m = mass, g = gravity	9.81m (kN)	3.71m (kN)
Wind load	1.0 kN/m^2	0.625 kN/m^2
Micrometeorites impacts	-	14 kN
Temperature	15℃ - 40℃	Average -63℃
Pressure	101.3 kPa	0.00636kPa (Less than 1% of Earth)

Based on the content from Table 15, the dead load (D = mg) where the m equal to mass and g equal to gravity. The dead load of Earth can be expressed into 9.81m and Mars can be expressed into 3.71m. From the expression, it is known that the dead load of Earth is 2.64 more than Mars. Therefore, the design requirement for dead load of Mars is lower than the requirement of Earth. The wind load and pressure of Earth also higher than Mars. The main consideration of Mars is the temperature. The average temperature of Mars is -63℃. The building materials of Martian building need to consider the effect of low temperature to sustain. This report proposes two options of model of modular construction method for Martian building that shown in Figure 13 and Figure 14.

Option 1: Container Structure

Figure 13: Revit model: Container Structure

Option 2: Modular Structure

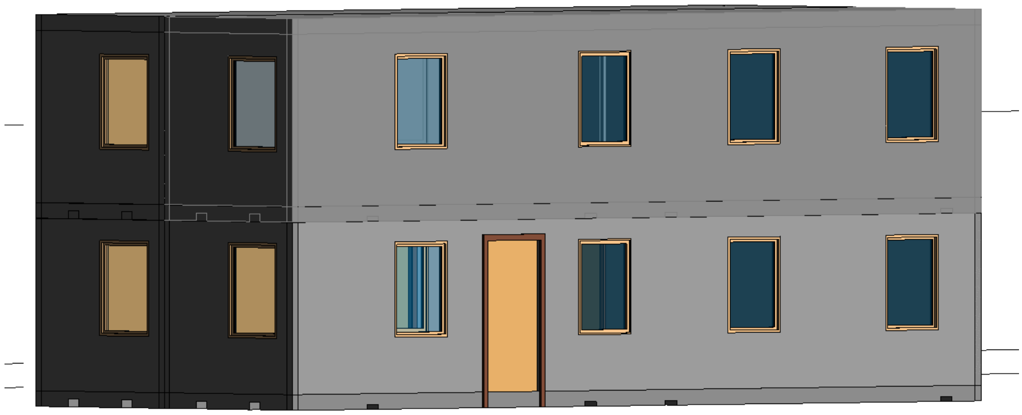


Figure 14:Revit model: Modular Structure

The dimension of each model is 12m(L) x 2m(W) x 2.6m(H). The mass of each model include payload capacity is around 24,000kg or 24tonnes. The modular structure can produce by steel frame, concrete panel, and concrete slab. The concrete categories can refer to Table 8 that shows the material composition, compressive strength, durability, and characteristics of different concrete apply in Mars.

To transport the container structure or modular structure to Mars, it may need a specific transportation to carry the structures. The specific transportation is shown in Figure 15.

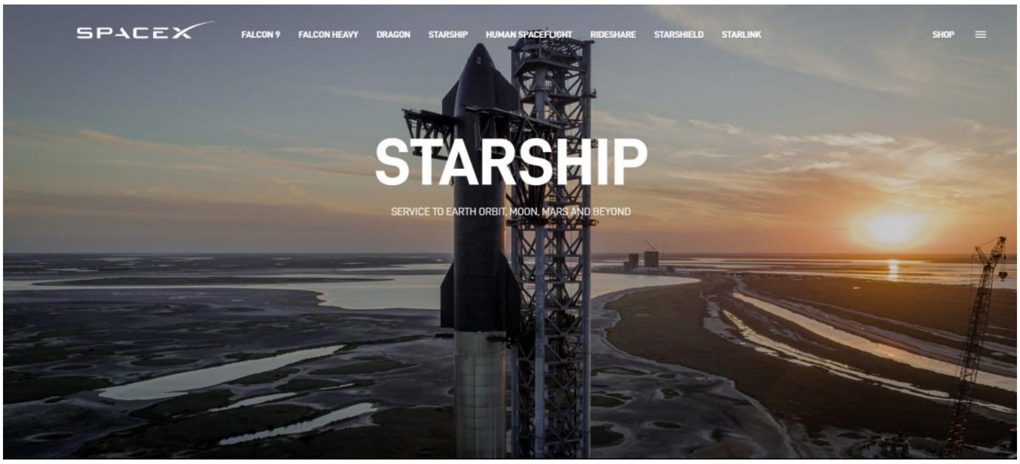


Figure 15: Starship (SpaceX, 2023).

SpaceX's creation, Starship, represents a completely reusable transportation system designed for ferrying both crew and cargo to diverse locations, including Earth orbit, the Moon, Mars, and beyond. It holds the title of the most potent globally engineered launch vehicle, able to transport up to 150 metric tonnes in a fully reusable mode and 250 metric tonnes in an expendable setup. Starship's remarkable dimensions include a height of 121 meters and a diameter of 9 meters. Figure 16 provides an overview of Starship (SpaceX, 2023).

The Starship consists of two primary sections: the upper component, referred to as Starship, and the lower part, named Super Heavy. Super Heavy serves as the initial stage or booster in the Starship launch system and is outfitted with 33 Raptor engines utilizing sub-cooled liquid methane (CH4) and liquid oxygen (LOX). Designed for full reusability, Super Heavy re-enters Earth's atmosphere and lands back at the launch site. The Starship itself is propelled by reusable methane-oxygen staged-combustion engines known as Raptor Engines.

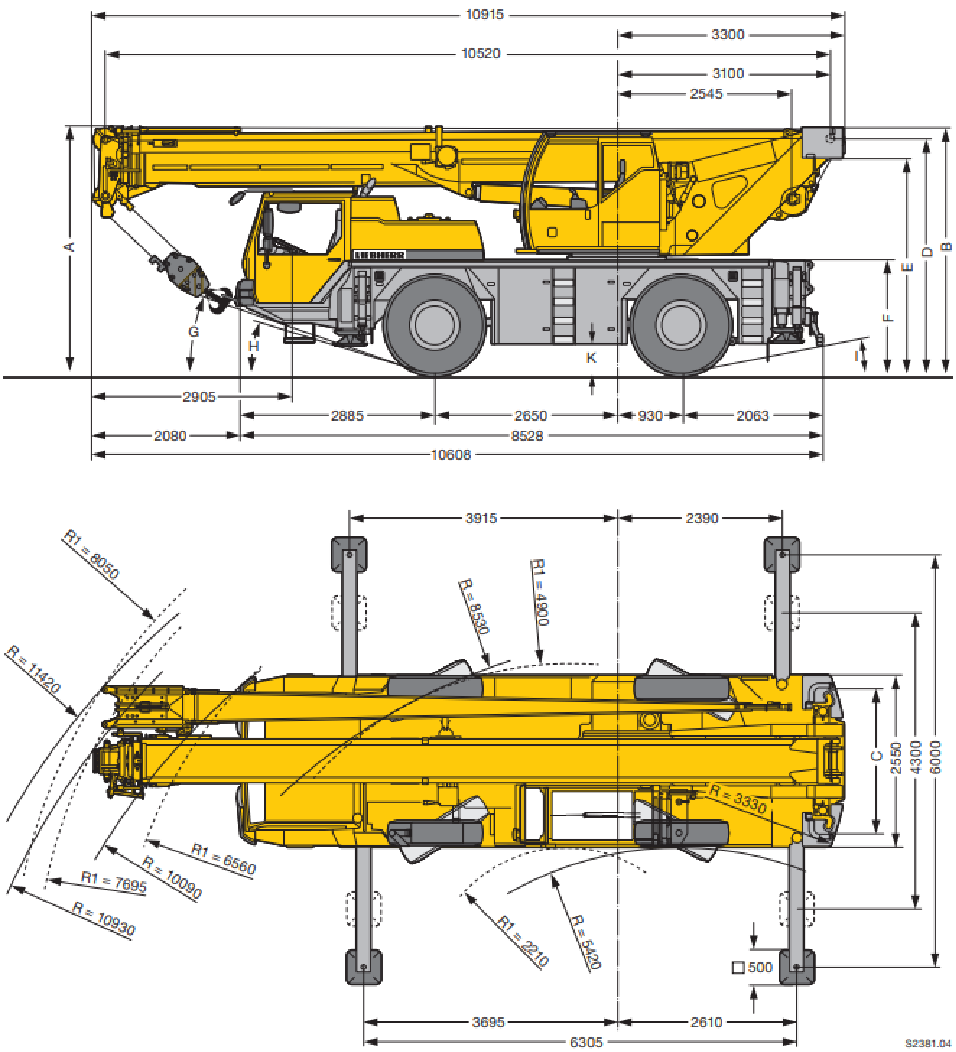
These engines, each delivering double the thrust of the Falcon 9 Merlin engine, drive the Starship system. Starship is set to feature six engines—three Raptor engines and three Raptor Vacuum (RVac) engines designed for the vacuum of space. In contrast, Super Heavy will be equipped with 33 Raptor engines, with 13 positioned centrally and the remaining 20 around the perimeter of the booster's aft end. Utilizing three Raptor engines in conjunction with RVac engines, which have a larger exhaust section and expansion nozzle, powers the Starship (SpaceX, 2023).

Figure 16: Starship Overview (SapceX, 2023).

Serving as the entirely reusable spacecraft and operating as the second stage in the Starship system, Starship is available in various configurations, incorporating an integrated payload section. Its design is tailored for the transportation of both crew and cargo to destinations such as Earth orbit, the Moon and Mars. Noteworthy is Starship's capability for point-to-point transport on Earth, enabling travel to any global location in under an hour. With dimensions standing at 50 meters in height and a diameter of 9 meters, Starship exhibits a payload capacity ranging from 100 to 150 tons in a fully reusable mode. Figure 17 provides an illustration of Starship (SpaceX, 2023).

Figure 17: Starship (SapceX, 2023).

To assemble the modular structure in Mars, it needs the specific equipment like crane to lift the modular structure up and put on the top of the modular structure to do the joining process. The 40-ton crane is proposed for the assembly of modular structure. The maximum lifting capacity is 40tonne. And the maximum lifting height and maximum radius are 44m with swing-away jib and 39m with swing-away jib. The 40tonne crane has the dimension of 10608mm(L), 4300-6000mm(W) and 3550-3600mm(H) without lifting. The specification of the crane is shown in Figure 18 (Bernard Hunter, n.d.).



R₁ = Allradlenkung · All-wheel steering · Direction toutes roues · Tutti gli assi sterzanti · Dirección en todos los ejes · Поворот всеми колесами

Maße · Dimensions · Encombrement · Dimensioni · Dimensiones · Размеры mm	A	A 100 mm*	B	C	D	E	F	G	H	I	K
14.00 R 25 (385/95 R 25)	3550	3450	3550	2113	3369	3074	1598	18°	16°	11°	375
16.00 R 25 (445/95 R 25)	3600	3500	3600	2101	3419	3124	1648	19°	17°	12°	425

* abgesenkt · lowered · abaissé · abbassato · suspensión abajo · шасси осажено

Figure 18: Specification of 40 tonne crane (Bernard Hunter, n.d.).

The joining technique of container structure can be bolting and welding techniques. Bolting is a more do-it-yourself alternative. To fasten the containers together, use strong bolts and nuts to provide a strong and secure connection and make sure tighten them appropriately. Strong and long-lasting connections can be made using welding, but skilled welding assistance is needed (UsedConex.com 2022). And the advantages of container structure are:

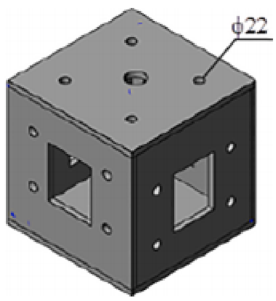
- Sustainability and low carbon construction of container homes
- Eco-friendly, green building
- Easy to transport

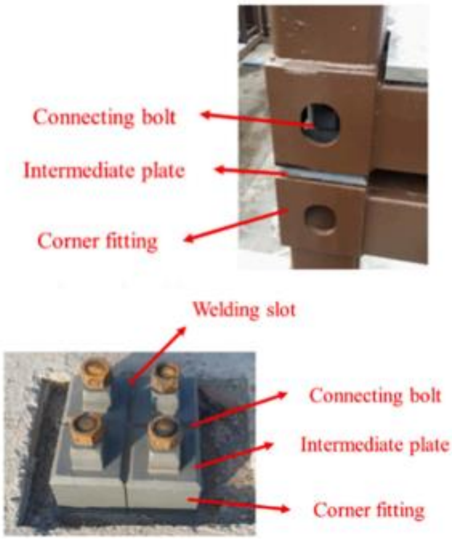
- Cost effective
- Low labor cost
- Structural stability
- Fast construction time
- Off-site construction
- Exterior insulation installed to withstand the weather conditions

(Carl Kenneth Gonzaga Hamilton, 2017; Islam et al., 2016; Yazarı et al., 2015)

Apart from that, the joining technique for modular structure may refer to Figure 4, Figure 5, and Figure 6. Other than that, the modular building connections used in the industry is shown in Table 16.

Table 16: Modular building connections used in the industry (Rajanayagam et al., 2021)

Connection	Illustration	Connectivity Features
Steel bracket connection		▪ Establish intermodular connections using bolts and steel square hollow sections. ▪ Ensure both vertical and horizontal connectivity.

Corner tie connector		▪ Ensure connectivity in both vertical and horizontal directions. ▪ Horizontally connect corner fittings assembled with intermediate plates, while vertically link corner fittings with bolts.

When using bolting joining technique in modular structure for Martian building, there may has fastener considerations. Bolting can be effective, but the type of fasteners used should be suitable for Martian conditions. Specialized coatings or materials resistant to Martian dust and weathering may be necessary. And the advantages of modular structure are:

- On time schedule
- Cost efficiency
- Safety on-site
- Product quality assurance
- Effective workmanship and productivity
- Good environmental performance

(Kamali & Hewage, 2016)

The costs that used for the costing analysis for Martian buildings are cost per module, cost of transportation of module, cost of transportation of equipment. The cost per module can refer to Figure 8 to get some idea (Tambichik et al., 2022). Besides that, Solid Horizon (n.d.) provide a shipping container home with the cost RM100,000 to RM250,000 that include the interior installation. According to Marspedia (2022), the extremely expensive estimation costing of materials is RM934,600 per kg. If the mass of each module is around 24,000kg, the cost of transportation of each module will be RM22,430,400,000. And the 40-ton crane will cost RM37,384,000,000. The estimation of costing analysis for Martian buildings is shown in Table 17.

Table 17: Costing Analysis for Martian buildings for one module.

Costing Analysis	**Cost (RM)**
Cost per module (include structure and installation)	250,000
Cost of transportation	22,430,400,000 + 37,384,000,000 = 59,814,400,000
Total	59,814,650,000 per module

From the Table 17 above, this is the costing analysis for one module only include the design cost and transportation cost that show total cost of around 60 billion. The fuel cost and the operation cost of Starship are not easy to estimate, it requires many of the equations to come out with the costing. Therefore, the costing analysis show in Table 17 is just a roughly idea for one module and this is not the final cost estimation. Other than that, the cost transportation of each people or worker also difficult to estimate because the worker needs specific training to survive in the space.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

In a nutshell, there are many concepts of construction method that propose for the Martian building. For example, In-Situ Resource Utilization (ISRU), 3D Printing, Pre-Fabrication, Biosynthesis, Radiation Shielding, Underground Construction, and Inflatable Habitats. The comparison between different types of construction method for Martian building are shown as above. Modular construction method provides an effective way to construct a complete building by joining all the module units. This can reduce the time of on-site construction and reduce the on-site labor. However, it requires specialist teams for the joining technique in the on-site construction. Design loading plays an important role in the design of the structure. Due to the different condition of the planet, the number of structural loads that we consider are different between Earth and Mars. Different kinds of concrete will give different results and characteristics. Therefore, selection of concrete is very important to provide a good structure that will not easily fail and is highly durable.

This paper provides 2 options of module such as container structure and modular structure that simulate by using Revit. To transport the container structure or precast structure to Mars, it may need a specific transportation to carry the structures which is Starship. Starship serves as the entirely reusable spacecraft and functions as the second stage in the Starship system. It is available in various configurations, featuring an integrated payload section, and is designed for transporting both crew and cargo to destinations such as Earth orbit, the Moon, Mars, and beyond. Notably, Starship possesses the capability for point-to-point transport on Earth, facilitating travel to any location worldwide in less than an hour. With dimensions measuring 50 meters in height and a diameter of 9 meters, Starship boasts a payload capacity ranging from 100 to 150 tons in a fully reusable mode. The costs that used for the costing analysis for Martian buildings are cost per module, cost of transportation of module, cost of transportation of equipment. The total cost of one module includes the equipment is around 60 billion which is still economical at this moment and the cost may drop in the future.

Modular construction should enhance these in the future to provide better performance. This method is a valuable contribution to the construction field which can reduce the construction time on-site. The comparison between modular construction system and other systems shows that modular construction system provides an efficiency of the time consumption in the construction. It is always said that time is money so the time consumption in the construction is reduced means that cost also reduced. Other than that, the manpower of modular construction system also a big advantage because the manpower of modular construction is saved means that the cost of the construction also reduced. Construction is always a big issue that has a bad impact on the environment. Therefore, modern construction methods like modular construction methods can reduce the impact on the environment. Modular construction method is better than the conventional construction method because it provides less waste generation compared to conventional construction method. Therefore, environmental pollution can be reduced.

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