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Selecting a Suitable Sustainable Construction Method for Australian High-Rise Building: A Multi-Criteria Analysis

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Abstract: The evolution of innovative construction technology and automation has rapidly transformed the construction industry over the last few decades. However, selecting the most efficient and sustainable construction technology for high-rise building construction is a critical factor in completing the project successfully. This requires a multiple-judgment-decision process relevant to cost, time, environment, sustainability, quality, etc. Thus, this research aims to identify the most suitable sustainable construction method for high-rise building construction in Australia. Three construction methods (i.e., automated building construction, aluminium formwork construction, and off-site construction) and robotic construction technology are reviewed in terms of economic, equity and environmental performance. A detailed multi-criteria analysis is conducted concerning the weighting calculated for each construction method, which aids in recommending a sustainable and cost-effective method. The analytical hierarchy process (AHP) is used as a multi-attribute decision-making tool to determine the weighting factors. The results show that the off-site construction method and robotic construction technique significantly improve the construction performance of high-rise construction in Australia. However, the finding is based on data obtained from a limited number of experts. Thus, a detailed case study with a greater number of expert opinions is needed to ensure the significance of the finding. However, the AHP-based approach method can be used to select sustainable construction alternatives for high-rise buildings.

Keywords: automated building construction; aluminium formwork construction; off-site construction; analytical hierarchy process; multi-criteria analysis

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1. Introduction

The Australian population has steadily increased by around 1.2% annually from 1989 to 2021 [1]. This increase demands more residential houses and high-rise buildings, primarily in metropolitan cities, such as Sydney, Melbourne and Brisbane. The high-rise buildings play a vital role in future urban construction and have been regarded as an effective solution to adopt high-population cities [2,3]. However, traditional high-rise construction faces problems, such as greater construction difficulty, lack of skilled labour, and safety risks from a dangerous construction environment [4]. Further, the current COVID-19 pandemic also limits the supply chain in both labour and materials [5]. Therefore, higher requirements, standards and policy developments are required to overcome these urban construction issues significantly, as available labour is decreasing [5–7]. Construction automation changes traditional construction's on-site labour-intensive and mess alignment into a rigid and efficient process [4,8–11]. A study by Bock [4] highlighted five possible aspects of future automation construction: robot-oriented design, robotic industrialisation, construction robots, site automation, and ambient robotics. In addition to robotic construction, currently, other innovative technologies are used for building construction, such as 3D printing [12], prefabricated building systems [5,13], digital twin technology [14] and drone technology [15]. These tech trends have gained advantages regarding time, cost, safety, and quality in the construction industry. This enables an essential direction for the future development of high-rise building construction. However, the application of these innovative technologies in Australian high-rise building construction is limited due to the limited resources and lack of knowledge and skilled labourers on this innovative technology.

Thus, this paper aims to identify the factor influencing the adoption and incorporation of these technologies and automation for the Australian high-rise construction industry to improve the cost, time, quality, and safety. This paper also proposes an approach to selecting suitable construction methods to improve the productivity of Australian high-rise building construction. The selection of suitable construction methods plays a significant role in the productivity, cost and environmental efficiency of high-rise building construction [16]. The inappropriate selection of construction methods will induce construction delays and increase the construction cost. Thus, selecting a construction method for high-rise buildings should involve a highly iterative multi-criteria decision-making approach via accounting for the cost, time, quality, safety, energy performance, etc. [17].

To achieve the aims of this study, a comprehensive review is conducted on the existing construction methods, technologies, and automation used in the construction industry globally to determine their advantages and constraints (Section 2). Further, a selected criterion-based multi-criteria-decision-making process is conducted to understand the risks, constraints and benefits of automation technology adoption. The analytic hierarchy process (AHP) is also presented for construction managers to systematically evaluate and select automation construction technology concerning the triple-bottom-line (TBL) framework (environmental, equity and economic). The paper utilises a well-accepted approach to assessing these construction methods quantitatively. It provides prospects to the construction industry in Australia to improve current conditions and move towards improved construction industrialisation.

2. Review of the Innovative Construction Technology

2.1. Automated Building Construction System (ABCS)

The construction system is also known as the "big canopy method", and the "jumping factory method" was introduced in Japan in the year 1983 [18] to improve labour productivity and a shortage of workers. The construction industry witnessed a massive decline in labour productivity, resulting in a considerable reduction in investment [18]. The construction industry in Japan also had a large number of labourer shortage to finish projects on time. In 1989, Obayashi construction framed the concept of the "Obayashi strategic integrated system" to automate building construction on site [18].

The ABCS consists of both a vertical and a horizontal delivery system, supported by the climbing system, which elevates the construction from floor to floor [19]. The "super construction factory" forms the main framework of the ABCS, consisting of the main walls and steel columns erected to reach the top [19,20]. The integrated ABCS consists of the production management system, equipment operation system and the machine control system, which controls the functions of an ABCS (Figure 1) [20]. The prefabricated members are transported according to the tags fixed on the members and placed at the required location. The working of the super construction factory is monitored and controlled in the central control room [18].

The ABCS significantly saves cost in time reduction and labour equipped in construction. However, this method proves costly with the amount of money spent on the scaffolding [18]. Even though the cost paid for scaffolding is high, there is a significant improvement in the work environment and safety, as the scaffolding is strong enough to withstand environmental loads [18]. ABCS was recently used in London's former Olympic village to construct two high-rise buildings (30 storeys and 26 storeys tall), which the Maze group implemented for GBP 9 million [21]. The London towers constructed by the Maze group adopted the same ABCS system, which has the "super construction factory" (SCF), a prebuilt factory where the whole construction process takes place for the high-rise buildings constructed [21]. Therefore, compared to the old conventional concrete construction, the factories of the ABCS could be reused for similar projects, resulting in significant cost savings for the builder [19].

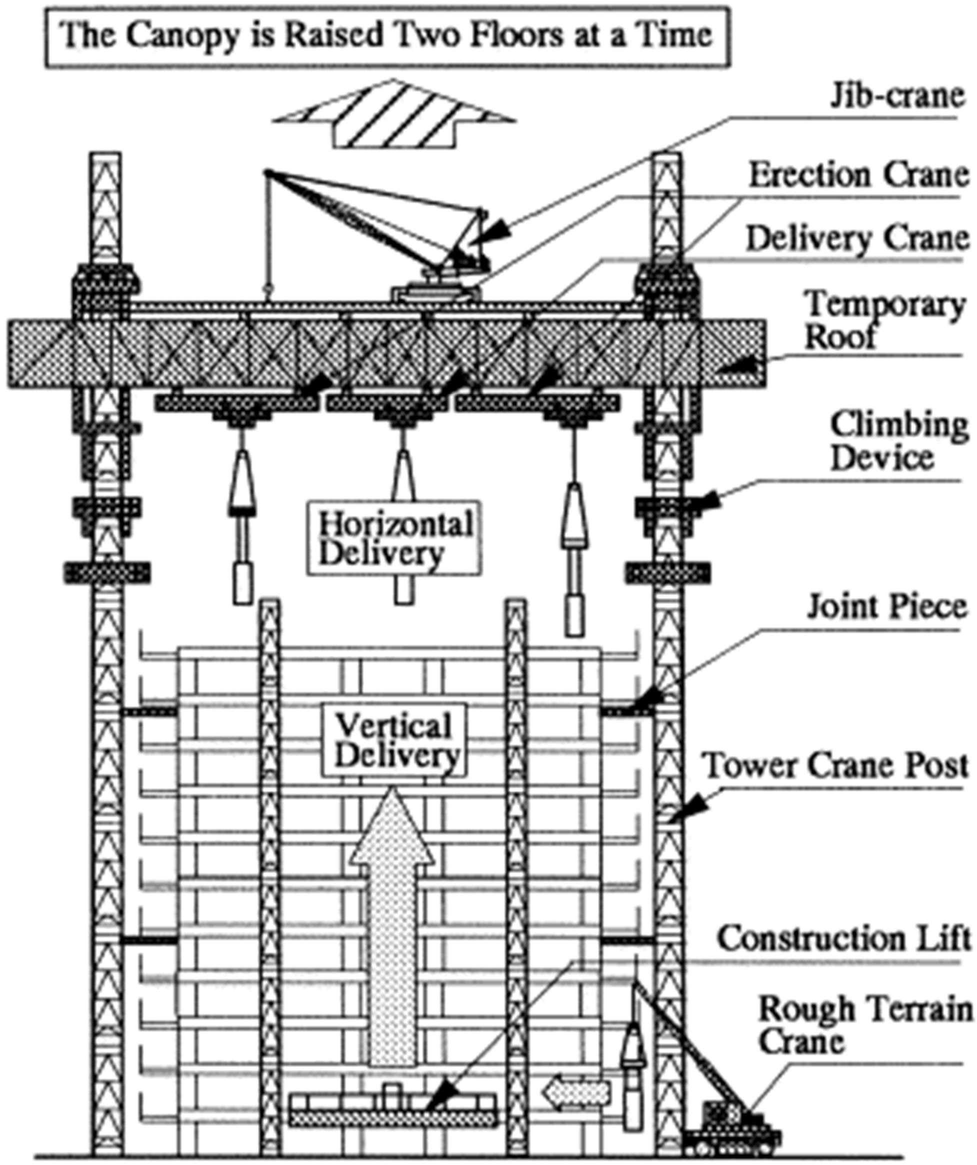

Figure 1. Big canopy ABCS [20].

Additionally, the London tower project by the Maze Group was completed at a rate of 55 h workweeks per floor [21]. Considering the total time taken for the construction of the building under the ABCS, as the number of floors increased beyond 20 stories, the ABCS system was found to be effective by reducing the total construction period of a 22-storey office building constructed by Obayashi construction [19]. After completing a high-rise building by Obayashi construction, the worker safety satisfaction survey indicated that workers had an overall positive experience in the super construction factory during the construction period [19]. The ABCS "super construction factory" significantly improves the working environment, as the work remains unaffected due to external environmental conditions, such as wind or rainfall [22]. Additionally, the measured noise outside the SCF was below 60 dB, which indicates that the work could be continued even during late hours. The temporary roof provided by the ABCS system offers a safe working environment for the workers by reducing the workload [22]. The labour productivity of the ABCS system was significantly higher than the conventional construction method when the Obayashi construction implemented the ABCS in a high-rise reinforced concrete building project [22].

2.2. Aluminium Formwork Construction System (AFCS)

A Malaysia based company known as Mivan Limited initiated the manufacturing process of aluminium formwork. Thus, the system is commonly known as "MIVAN Formwork". The plastic form of fresh concrete needs a mould to acquire the desired shape (such as walls or slabs). The usage of such a mould is known as formwork. In the conventional formwork method, timber plywood panel is fabricated on-site and tied to form the required shape, into which concrete can be poured. A study by Karke and Kumathekar [23] compared the capability of conventional formwork and aluminium formwork methods. The comparison proved that timber formwork degrades quickly with repeated use and is less capable of withstanding wet concrete pressure due to the poor structural properties [23]. Another study by Hurrah and Danish [24] showed that a 4 mm thick aluminium sheet mould can resist 7–8 tonnes of load per square meter. Further, their study highlighted that the construction of each floor is typically finished in 7 days. Moreover, the maintenance cost is also meagre since all the building components are built in high-strength concrete [24].

The AFCS helps increase the speed of construction, which reduces the overall project duration and the associated cost [25]. Another comparison between timber and aluminium formwork showed that the concrete spillage is lower in aluminium formwork than in timber formwork due to there being fewer joints in aluminium formwork [26]. Furthermore, the thin sheets of aluminium panels help deliver a smooth finish on the walls before plastering and tend to eradicate the plastering of walls, slabs, etc. [26]. This monolithic operation of casting both walls and slabs together helps eliminate the construction of beams and columns, which further improves aesthetics.

Another study by Thiyagarajan et al. [27] compared the performance of AFCS with other formwork systems, such as prefabrication technology and tunnel formwork technology. The prefabrication technology eradicates the formwork by pre-casting all the building components, such as wall panels and roof/floor panels in off-site, which reduces the material cost. The tunnel formwork and aluminium formwork are very similar, but the latter uses steel form instead of aluminium form to construct the components of the building. Safety, duration, quality and cost are the significant factors that are used for comparison in analysing the buildings constructed with the respective methods. The comparison proves that the duration of construction can be reduced to 40–45% by using AFCS. The initial cost for aluminium formwork is high compared to conventional formwork, but with the reduced construction duration, the overall cost can be minimised compared to the conventional formwork [28].

The duration of construction for a 12-storey residential building can be reduced up to 45% with a typical floor cycle of 7 days by aluminium formwork [24,29]. The cost of construction for aluminium formwork is 25% lower than a conventional system, but this difference in cost is applicable only when the same aluminium forms are used repeatedly [29]. Furthermore, all the components are manufactured using thin aluminium sheets, which improves the quality of work for the labourers as well as eliminating the necessity for skilled labourers [23]. However, any type of formwork requires scaffolding, which increases the safety risks for labourers [30]. The scaffolding requirement for aluminium formwork should have proper safety standards. A recent incident in Sydney occurred when two labourers were injured heavily due to scaffolding collapse and one labourer lost their life [31]. The construction site requires space for storing the aluminium forms, which leads to congestion if not appropriately addressed. The aluminium formwork generates less waste since the aluminium forms can be recycled entirely after their usage is over [32]. The wastage of material is lower due to the simplified installation process of the aluminium formwork [33].

2.3. Off-Site Construction (OSC)

Off-site construction (OSC) is not a novelty, and the original concept can be traced back thousands of years. Today, OSC involves designing and fabricating standardised structure components away from the work site, usually in a controllable factory environment, and then transporting them to the site for assembly [13,34–36]. Gibb [37] classified OSC into four levels: component manufacture and sub-assembly, non-volumetric pre-assembly, volumetric pre-assembly, and modular buildings. This OSC shows significant potential benefits in both construction and the environment compared to conventional in situ construction systems [36,38,39]. Furthermore, this OSC is recognised as a cost-effective alternative to transforming the construction industry [39,40].

The OSC typically shortens the construction period by half compared with the in situ casting construction method and improves the time certainty [41]. Navaratnam et al. [36] concluded that the OSC cost is lower, even though the initial cost is higher than traditional construction. Furthermore, the OSC method uses less labour and resources [38]. Additionally, OSC enables a significant improvement in project quality because most of the work is undertaken in a controllable factory environment [42]. Greater safety is another advantage, as some high-risk operations can be effectively managed and controlled in a factory [43]. Navaratnam et al. [36] further stated that approximately 80% of safety issues are eliminated with OSC. As widely discussed in the academic community, there are also some environmental benefits, such as better energy performance of constructed houses and waste material utilisation during the construction process [34–36,44]. However, the OSC accounts for only 3–5% of the estimated AUD 150 billion in Australian construction [5].

A survey conducted by Pan et al. [45] highlighted the critical obstacles to applying OSC among U.K's leading housebuilders. Their study concluded that higher initial capital cost and a complex, critical relationship between on-site and off-site activities are significant barriers to adopting OSC over traditional construction. The stubborn industry structure, culture, and lack of related regulations are also considered to slow down the adoption degree of OSC. Skilled labour shortages and limited knowledge of OSC are specifically highlighted in the Australian construction market [36,40,46].

The OSC method reduces the labour cost by about 25% compared to the conventional construction method [47,48]. The improvement in construction quality is another benefit of the OSC, though no academic literature approves that with strong evidence. In a survey conducted by Goodier and Gibb [49], nearly half of construction practitioners ranked it as a core competency. With automation in the factory environment, the quality can be ensured to be consistent and supervised [5,36]. The manufacturing line makes it possible to produce building elements as industrialised products. In terms of safety, the conventional construction method poses unpredictable risks to the labour on site. With prefabrication, 80–85% of the risk can be mitigated because the work is happening in a controlled factory, which directly decreases the reported accident rate [41,50].

Furthermore, the OSC method eliminates the negative impacts on the surrounding area. It can inherently be undertaken in limited space, especially in a high-density urban area. Meanwhile, the noise generated during the construction process is lessened and will not have too much impact on the life of the surrounding residents [36]. Conventional construction consumes substantial resources and generates considerable waste and pollution. However, the OSC fits well with sustainable development, as it transfers most of the work into a controllable factory, reducing construction waste from 54.6 tonne/100 m^2 to 1.5 tonne/100 m^2. Moreover, it reduces about 50% of greenhouse gas emissions and saves around 30% of energy consumption [51–53]. In addition, effective collaboration can also be achieved within the project, and resources in all areas can be fully utilised to optimise the allocation of resources and reduce resource consumption.

2.4. Automation in Construction—Robotics

Introducing robotics into the construction industry will alleviate construction problems, such as worker safety, construction delay and construction quality [8]. In recent years, digital fabrication has become an innovative technology in the construction industry. One of the benefits is creating a highly differentiated structure with the minimal use of materials in the planning stage [54]. Figure 2 shows the in situ fabricator (IF) which is an on-site construction robot designed with a series of functions, and it is equipped with an end-effector of 1–5 mm positioning accuracy [54]. Moreover, it has flexible mobility in a typical construction site with various obstacles. Furthermore, novel algorithms are established to align with the CAD model of the desired structure and precisely locate the end-effector to the reference frame of the structure. The system can provide real-time feedback to tackle inaccuracies during the construction stage [10]. A mesh mould is the main component of the digitally fabricated wall (Figure 3) built by IF [10], which plays the role of both the basic shape of the wall and the reinforcement structure of concrete formwork [55]. Compared to the conventional wall, this fabrication method eliminates material waste in construction.

The IF also displays the possibility of a continuous digital process from design to construction. The free-form property of steel meshes provides several benefits for construction. For instance, a vision system installed in IF can detect material tolerance when building up the desired structure and generate a negotiable solution based on the input data. Once the steel structure is finished, concrete is ready to fill up with the dense mesh through a nozzle with the aid of compaction by workers, followed by the step of manual trowelling process [10]. Nevertheless, it is inevitable for IF to have a few limitations [54]. In order to ensure a high positioning accuracy, the design of joints and links is heavy. Thus, the payload-to-weight ratio (PWR) is relatively low (i.e., 40 kg: 400 kg). Additionally, the machine's base is heavy to avoid overturning. Consequently, it increases the difficulty of transporting and the safety risk of operation. In another aspect, without vibration-damping mechanical elements, the gearboxes of the machine are likely to wear out after long runtimes or being used every day. Thus, next-generation IF is to be redesigned to deal with these problems.

Wearable robots have become popular in the construction industry for labourers who need to undertake heavy manual work [11]. Several kinds of wearable robots, such as the mounted arm exosuit (i.e., ZeroG arm), used to make heavy hand tools almost effortless by rendering them weightless [56,57]. Workers who are equipped with ZeroG arm can save time and money by getting the work done faster and protecting from injury and strain. The EXO vest is a backpack for workers, lifting their arms with 5 to 15 pounds of lift assistance per arm [56]. It is all mechanical and weighs under 10 pounds so that they can wear it comfortably all day, and this vest is perfect for a variety of overhead applications, such as manufacturing. The wearable robots reduce the potential safety risks to the operator, such as musculoskeletal disorders [56,57]. In addition, due to the assistance of mechanical equipment, the number of required labourers can be reduced. Furthermore, the tool also results in a higher quality of work because it helps workers utilise their skills with precision. Consequently, reducing the amount of rejected parts and construction time. Furthermore, wearable robots provide better performance with lower energy consumption [56,57].

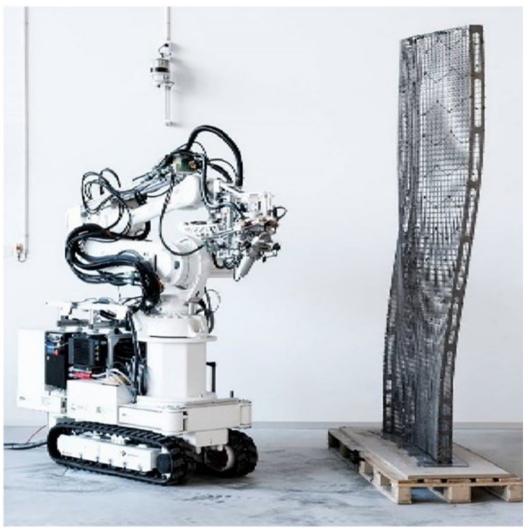

Figure 2. The in situ fabricator [58].

Figure 3. Double-curved mesh filled with concrete [10].

Research on mesh mould walls was conducted in the DFAB HOUSE in Dubendorf, Switzerland. A 4.39 m^3 concrete wall was analysed in terms of environmental and economic aspects by comparing it with a conventional wall [58]. In terms of the economic aspect, the number of labourers used in the digital fabrication wall (i.e., 8) is less than that used to construct a conventional wall (i.e., 10). In addition, the average daily crew cost of a mesh mould wall is much lower than the same type of cost for a conventional wall, costing USD 784 and USD 1272, respectively. Nevertheless, there is a capital cost for an industrial robotic arm, about USD 125,000, with an expected lifetime of 90,000 h. Furthermore, the cost of a straight wall made by digital fabrication is three times higher than the conventional method, which is 5023 USD/m^3. However, in the case of a complex double-curved wall, a conventional wall soars to 12,262 USD/m^3, while the cost of a mesh mould wall only increases to 5288 USD/m^3. Thus, it is evident that the robotic construction method is far cheaper in high-complexity wall fabrication.

Special formwork for double-curved walls is the reason for the high cost of the conventional method. On the other hand, the time cost is also a concern. In the case of a straight wall, the construction time of conventional and digital fabrication are 5 and 15.63 h/m^3, respectively. With respect to the complex wall, the time cost of a conventional wall soars to 15.02 h/m^3, while the digital fabrication method only increases to 16.93 h/m^3. In conclusion, digital fabrication has a significant benefit in constructing highly complex walls. In terms of environmental assessment, it is reported that concrete mixtures for mesh mould walls generate 20% less CO_2 emissions than conventional wall mixtures to reach the same structural performance [59]. Furthermore, a digitally fabricated wall (DFW) contributes 40% more CO_2 emissions when the thickness is 20 cm. However, CO_2 emissions from 10 cm DFW are 12% lower than those of a similar size of the conventional wall. A break-even point of CO_2 emissions exists when the thickness of DFW is 12 cm. The steel volume fraction (r_{MM}) also impacts the CO_2 emissions of DFW construction. The best scenario of a mesh mould wall is characterised by a minimum r_{MM} of 0.5% and a minimum thickness of 10 cm, which produces 20% less CO_2 than the conventional wall. However, the compression strength of DFW is also higher than the conventional wall in this situation. Furthermore, due to the heavyweight of IF, it increases the operation's transportation difficulty and safety risks [54].

3. Method

The method used in this investigation is shown in Figure 4. This helps to identify the current state of construction technology and find the appropriate construction method, technology and automation for the Australian high-rise building construction industry.

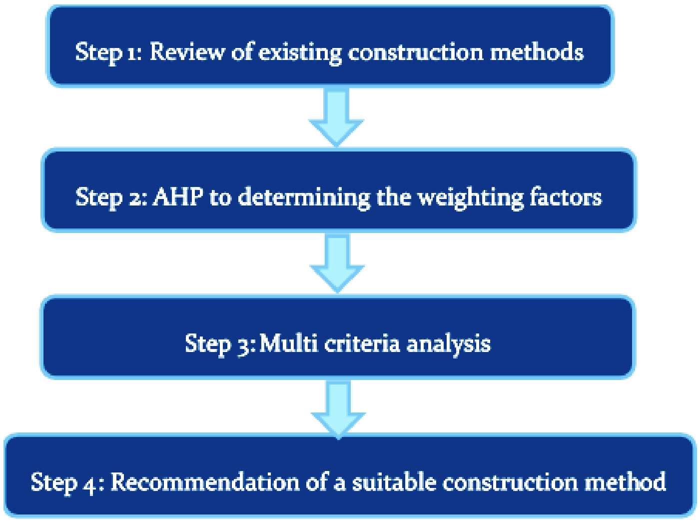

Figure 4. Steps involved in this investigation.

3.1. Multi-Criteria Analysis (MCA)

The selection of construction methods is one of the most important factors affecting construction performance [60,61]. This is a complex decision-making process, and project leads need to think over multiple elements and criteria [62]. In most cases, the activity lacks enough studies and it is generally based on previous experience. The construction time, cost, and quality are the most relevant concerns in selecting a suitable construction method [63,64]. Several other factors, for example, safety, available resources, ambient environmental conditions, technical feasibility, and skilled workforce supply, should be considered [62,65]. Table 1 summarises the indicators for selecting the construction method from the previously discussed literature studies (Section 3). Chen et al. [66] further developed a sustainable criteria system in accordance with TBL for construction method selection in concrete buildings.

An AHP method is used in this study to identify the ranking of the most influential factors that induce the inherent risk of a high-rise construction project completion, as it enables the explicit ranking of perceptible and imperceptible factors against each other to resolve conflict [73–79]. This method combines both qualitative and quantitative approaches to solve a complex problem by using expert opinion [76,80]. Furthermore, this AHP method is applicable to using a limited number of data samples [76,80,81]. Previous studies have used the AHP approach with a limited number of expert participants (e.g., 5 [81], 5 [82], 7 [83]). Thus, this study used the AHP method to determine the weighting factor and identify the sustainable construction method for high-rise buildings.

In the first step of AHP, define the problem and the hierarchy structure based on the criteria specified in Table 1. Then, in the second step, construct the pairwise comparison matrix based on the expert feedback. Then calculate the weighting factor and determine the consistencies. This study established four levels of hierarchy structure using the criteria detailed in Table 1 to determine the weighting factor for the criteria listed in the hierarchy diagram (Figure 5).

Then the criteria (Table 1) were evaluated by building construction experts, including three structural engineers, two project engineers and three construction managers (Appendix A), to establish the pairwise matrix. The pairwise comparison matrix was used to represent the relative important level of each indicator. The numerical number scale 1 to 9 was used to represent an important scale, which is similar to that proposed by Saaty and Vargas [74]. The number 1 represents "equal importance", 3 and 5 represent "immediate importance" and "strong importance", respectively, and 7 and 9 are "very strong" and "extreme" importance, respectively. The primary criteria matrix (E) is defined in Equation (1). The primary criteria economic (E1), equity (E2) and environment (E3) and the important relationship between the two criteria (e.g., E12 and E21) can be treated as reciprocal. The weight vector can be derived via adding a normalised score on each row of matrix E. The normalised score was derived via the totalling numbers in each column, and then each entry in the column was divided by the column sum to yield. The evaluators that gave the importance-scale indicators for the primary and sub-criteria are detailed in Table A1 in Appendix A. Using the assessor indicators value in Equation (1), the weighting of the primary indicators was derived as 63.3%, 26% and 10.9%, respectively for economic, equity and environment. A similar method was used to derive the weighting of sub-criteria (Equation (2)).

Table 1. Criteria for selecting construction method.

Criteria	**References**											
	[67]	[68]	[16]	[65]	[69]	[70]	[62]	[71]	[17]	[72]	[66]	[63]
Time	X	X	X	X	X	X	X	X	X		X	X
Cost	X	X	X	X	X	X	X	X	X	X	X	X
Quality			X	X	X	X	X	X				
Risk									X			
Resource availability			X	X	X				X	X		
Maintenance										X		
Production rate								X		X	X	X
Physical characteristics of the element to build	X	X		X				X				
Construction method characteristics	X	X	X			X				X	X	X
Environment		X			X							
Site characteristics			X				X					
Safety			X		X			X			X	X
Minimum site disrupts			X		X							
Workforce competences				X								
Stakeholder	X											X

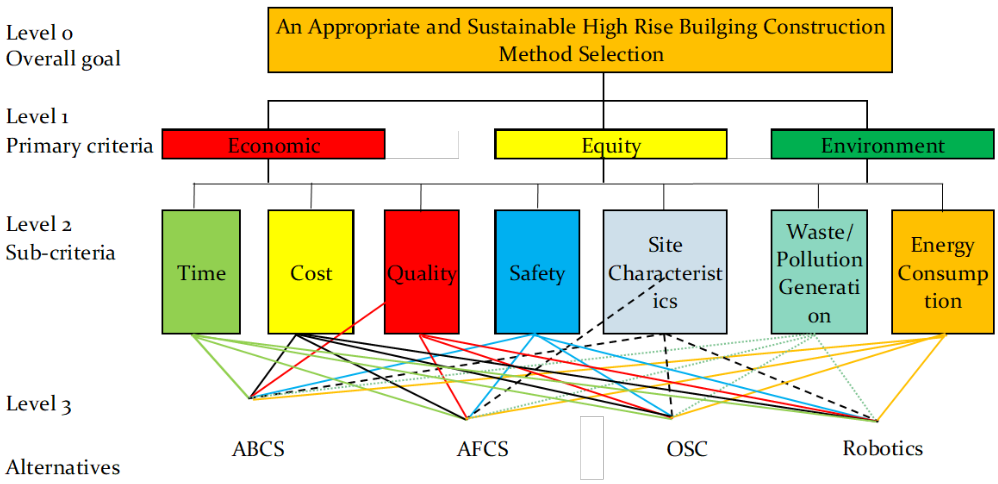

Figure 5. The hierarchy for selecting the most appropriate construction method for high-rise building.

$$E = E_{ij} = \begin{array}{c} \\ E1 \\ E2 \\ E3 \end{array} \begin{array}{c} E1E2E3 \\ \begin{bmatrix} 1 & E_{12} & E_{13} \\ 1/E_{12} & 1 & E_{23} \\ 1/E_{13} & 1/E_{23} & 1 \end{bmatrix} \end{array} \begin{array}{c} Weight\ Vector \\ \begin{bmatrix} w1 \\ w2 \\ w3 \end{bmatrix} \end{array} = \begin{array}{c} \\ E1 \\ E2 \\ E3 \end{array} \begin{array}{c} E1 \quad E2 \quad E3 \\ \begin{bmatrix} 1 & 3 & 5 \\ 0.33 & 1 & 3 \\ 0.20 & 0.33 & 1 \end{bmatrix} \end{array} \begin{array}{c} Weight\ Vector \\ \begin{bmatrix} 0.633 \\ 0.260 \\ 0.109 \end{bmatrix} \end{array} \quad (1)$$

$$B = \begin{array}{c} \\ B1 \\ B2 \\ B3 \\ B4 \\ B5 \\ B6 \\ B7 \end{array} \begin{array}{c} B1 \quad B2 \quad B3 \quad B4 \quad B5 \quad B6 \quad B7 \\ \begin{bmatrix} 1 & 1 & 1 & 1 & 3 & 3 & 5 \\ 1 & 1 & 3 & 1 & 5 & 1 & 9 \\ 1 & 0.33 & 1 & 1 & 1 & 3 & 7 \\ 1 & 1 & 1 & 1 & 1 & 3 & 9 \\ 0.33 & 0.2 & 1 & 0.2 & 1 & 1 & 3 \\ 0.33 & 1 & 0.33 & 0.33 & 1 & 1 & 5 \\ 0.2 & 0.11 & 0.14 & 0.11 & 0.33 & 0.2 & 1 \end{bmatrix} \end{array} \begin{array}{c} Weight\ Vector \\ \begin{bmatrix} 0.194 \\ 0.246 \\ 0.157 \\ 0.185 \\ 0.096 \\ 0.097 \\ 0.025 \end{bmatrix} \end{array} \quad (2)$$

To ensure reasonable judgements, a consistency test was performed. The consistency index (*CI*) and consistency ratio (*CR*) are both required not to exceed 0.1 to accept the outcomes. The *CI* and *CR* for the primary criteria were 0.028 and 0.048, respectively. The sub-criteria analysis also produced acceptable judgements, as the *CI* (0.099) and *CR* (0.076) were less than 0.1.

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad (3)$$

$$CR = \frac{CI}{RI} \quad (4)$$

where λ_{max} is the dominant eigenvalue among all the eigenvalues of the matrix, n is the matrix size, and *RI* is the random index dependent on the matrix size. In this analysis, *RI* is 0.58 and 1.32, respectively, for primary and sub-criteria.

3.2. Results

Figure 6 shows the weighting factor derived from the AHP process for the sub-criteria. This figure illustrates that cost occupies the highest weighting percentage, followed by construction time, health and safety, and quality. The health and safety of construction also account for a higher percentage (18%) than site characteristics. Waste/pollution generation and energy consumption are given less priority in the multi-criteria analysis (MCA) of construction methods and techniques.

The predicted weighting factor was used with the MCA score scale (Figure 7) to compare the sub-criteria of each construction method with the conventional construction method. The conventional construction method was at the stratum level for the comparison. Thus, the scale score was to be taken as zero (neutral). Based on the neutral, the other score numbers of 1, 2, 3 and 4 represent 25%, 50%, 75% and 100% reduction (−) or increases (+) considering the sub-criteria, compared to conventional construction.

Table 2 shows the MCA of the construction method for high-rise buildings. The first column in the table is for the sub-criteria established in the AHP hierarchy structure (Figure 5). The weighting factor (Figure 6) determined from AHP for each sub-criterion is presented in the second column. The score in the table was given by the 10 construction experts (3—structural engineers, 2—architects, 3—planning engineers, 2—project managers) who have over 10 years of experience in the construction industry. Furthermore, their judgement was compared with the literature review information discussed in Section 3. It should be noted that the score used in the MCA was higher in the population than the score given by assessors.

Table 2 indicates that the OSC method was Australia's most feasible construction method for high-rise building construction. Further, ABCS and AFCS also enable significant benefits over conventional construction methods. Furthermore, introducing robotic techniques into conventional construction improves the construction performance and reduces the cost and time (Table 3).

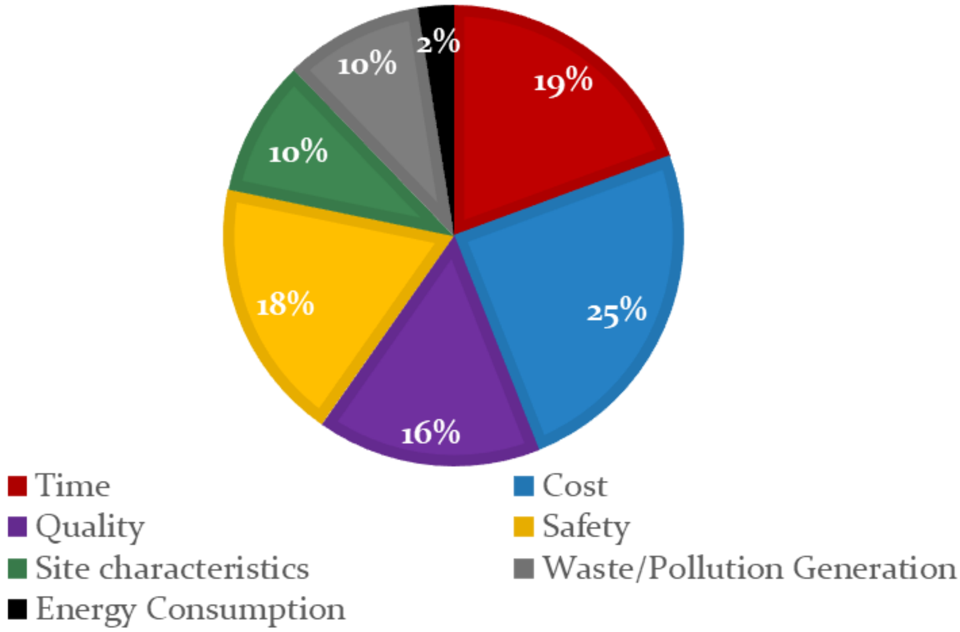

Figure 6. Weighting distribution for sub-criteria.

Figure 7. MCA score scale.

Table 2. MCA of the construction method for high-rise building.

Criteria	Weighting Factor	ABCS		AFCS		Off-Site Construction	
		Score	Weighted Score	Score	Weighted Score	Score	Weighted Score
Time	0.194	−3	−0.581	−3	−0.581	−4	−0.775
Cost	0.246	−1	−0.246	−1	−0.246	−1	−0.246
Quality	0.157	−3	−0.472	−2	−0.315	−2	−0.315
Safety	0.185	−3	−0.555	0	0.000	−3	−0.555
Site characteristics	0.096	−2	−0.191	−1	−0.096	−3	−0.287
Waste/pollution generation	0.097	−1	−0.097	−2	−0.195	−3	−0.292
Energy consumption	0.025	2	0.050	−2	−0.050	−2	−0.050
TOTAL			−2.093		−1.482		−2.519

Table 3. MCA of the robotic construction techniques.

Criteria	Weighting Factor	Robotics			
		In Situ Fabricator		Wearable Robot	
		Score	Weighted Score	Score	Weighted Score
Time	0.194	−3	−0.581	−2	−0.387
Cost	0.246	−3	−0.739	−2	−0.493
Quality	0.157	−2	−0.315	−2	−0.315
Safety	0.185	1	0.185	−2	−0.370
Site characteristics	0.096	0	0.000	0	0.000
Waste/pollution generation	0.097	−1	−0.097	0	0.000
Energy consumption	0.025	−1	−0.025	−2	−0.050
TOTAL			−1.571		−1.614

4. Discussions

The results from the MCA presented in Tables 2 and 3 display the relative applicability and effectiveness of the construction method and robotic construction technology. The economic factor is the most important factor, which accounts for about 63% of the weighting and is dominant in decision making. Further, this is followed by equity and environmental which account for about 26% and 11%, respectively, in the weighting of the decision making. The financial performance is the most direct judgement basis and is easy to account for. The sub-criteria time, cost, quality, and safety accounted for over 75% weighting of the total variance, while site characteristics, waste/pollution generation, and energy consumption accounted for 9.6%, 9.7% and 2.5%, respectively.

Table 3 indicates that the OSC method enables the highest benefits compared to the other construction method, which indicates that it is the most appropriate construction method for the Australian construction market when considering these seven sub-criteria. A similar observation was found in the previous studies [5,34–36]. Their studies highlighted that modular construction has numerous advantages (construction time, quality, waste, energy, etc.) over conventional construction.

The construction time, safety, quality and cost performance of all three construction methods were significantly more efficient than the conventional construction method. This finding was agreed with previous studies by Ghangus [26], Navaratnam et al. [5], and Kudoh [18]. Although the initial cost of the ABCS, OSC and AFCS are higher than the traditional construction method due to the initial research and technical development, the impact will be reduced because of cost amortisation in the long term and the large scale of the project. The quality improved variably because of differences in focus on construction activities and the working environment. OSC benefits from its flexibility because most of the work is undertaken in a controlled factory environment, receiving the most positive impact on site characteristics. For the environment, prefabrication shows huge environmental advantages due to a recycling economy in the factory. It eliminates at least 70% of landfill waste compared to conventional construction [43]. Other methods also reduced the waste/pollution to variable degrees but not significantly.

Robotics in construction is a newly developing area. Many construction robots are designed to complete a single task, for example, monitoring drones and robotic arms. Indeed, it accelerates construction activity and reduces labour costs [8,54]. This study also found similar observations (Table 3). However, some performance indicators were not effectively and precisely measured. This is because the participants had limited knowledge of these technics. In situ fabrication and other digital fabrication may generate high economic and environmental benefits in constructing high complexity walls or other building elements [58]. However, considering the current technology and the complexity of construction, robotics in construction is still not viable for wide commercial use. Future development is necessary to resolve the labour shortage. A relative quality and quantitative assessment in this paper provides an overview for selecting the construction trend in the Australian construction industry.

5. Conclusions

The review of construction methods, innovative technology, and automation used in the construction industry is intended to be a holistic approach towards bringing a sustainable approach to the construction industry. To identify the most efficient construction method for high-rise building construction in Australia, this study conducted a comprehensive review of existing construction methods and innovative automation technics.

Three main construction methods and robotic construction techniques were reviewed in relation to the benefits in the construction phase. Three primary criteria (i.e., economic, equity and environmental) corresponding to TBL and seven sub-criteria were identified in this study to evaluate and identify an appropriate construction method for the Australian high-rise construction industry. The AHP approach, a well-accepted multi-criteria-decision-making process, was employed to determine the weighting of each criterion.

The results show that the OSC method has a high potential to enhance the efficiency and performance of high-rise building construction in Australia. Furthermore, the ABCS and the AFCS could be incorporated into prefabrication to create an ideal construction method for the Australian high-rise construction industry. Further, the results show that adopting robotics in construction techniques in the Australian construction industry will reduce the construction time and increase work safety and quality. However, robotics in the Australian construction industry is yet to be realised in relation to the construction method and equipment used. Robotics techniques are still in the stage of infancy, where automation is yet to be explored.

Furthermore, the results derived in this paper were based on the previous research and the feedback provided by a limited number of construction experts. Further, the expert participants in this research have limited knowledge of robotic techniques. Thus, future research is needed to ensure the efficiency of the finding from this study. However, the proposed MCA method can be applicable to find the most suitable construction method and techniques.

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Appendix A

The important levels of the primary and sub-criteria of the AHP hierarchy structure was obtained from the construction experts and detailed in Table A1. These data were used to establish the pairwise matrix.

Table A1. Assessment results of the main and sub criteria related the selection of construction method.

Criteria	Assessor								Selected Important Level
	1	2	3	4	5	6	7	8	
Economic (E1) vs. Equity (E2)	1	5	5	7	5	1	5	5	5
E1 vs. Environment (E3)	5	9	5	1	5	5	5	5	5
E2 vs. E3	5	3	3	3	3	7	1	3	3
Time (B1) vs. Cost (B2)	1	1	1	5	3	1	1	7	1
Time (B1) vs. Quality (B3)	3	7	1	1	1	1	5	1	1
Time (B1) vs. Safety (B4)	9	1	1	1	3	1	3	1	1
Time (B1) vs. Site characteristics (B5)	1	3	3	1	1	3	3	3	3
Time (B1) vs. Waste/Pollution Generation (B6)	5	3	3	3	1	5	3	3	3
Time (B1) vs. Energy Consumption (B7)	1	1	1	5	5	5	5	5	5
B2 vs. B3	3	3	3	3	7	3	5	7	3
B2 vs. B4	3	1	3	1	1	1	1	4	1
B2 vs. B5	5	5	5	7	5	7	5	5	5
B2 vs. B6	1	3	1	1	3	1	1	3	1
B2 vs. B7	5	9	7	9	9	9	9	9	9
B3 vs. B4	1	3	1	1	1	3	5	1	1
B3 vs. B5	3	3	1	1	1	1	1	5	1
B3 vs. B6	3	5	3	7	3	3	3	3	3
B3 vs. B7	9	7	7	5	5	7	7	7	7
B4 vs. B5	1	1	3	1	3	1	1	3	1
B4 vs. B6	3	3	1	1	5	3	3	3	3
B4 vs. B7	7	7	7	9	9	9	9	9	9
B5 vs. B6	1	1	3	1	1	1	1	3	1
B5 vs. B7	3	3	5	5	3	3	3	5	3
B6 vs. B7	9	9	5	5	5	5	5	7	5

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