Case studies in modular prefabrication: comparative analysis and discoveries

Koorosh Gharehbaghi\textsuperscript{1}, Erica Mulowayi\textsuperscript{1,\ast}, Farshid Rahmani\textsuperscript{1} and David Paterno\textsuperscript{1}

\textsuperscript{1}RMIT University, Melbourne, Australia

\textsuperscript{\ast}E-mail: erica.mulowayi@rmit.edu.au

Abstract. While prefabrication is the process where parts are manufactured off-site, modular construction on other hand is the utilisation of parts along with their installation to form a complete structure, such as a building. The aim of this paper is to compare case studies in prefabrication including modular construction. Subsequently, this paper reviewed five case studies around the globe. The comparison of these case studies showed that China had the fastest construction rate by manufacturing steel modules off-site. This was presumably due to the significant use of Advanced Modular Technology (AMT). Such new technique can potentially be the next era of prefabrication construction in high-rise construction. Particularly, the corporations which are either exploring or are using modular prefabrication should utilise AMT to enhance the design technique and assembly of prefabricated units.

1. Introduction
Globally, industries are continuously looking for new technologies and innovations to maximise the quality of their products [1-3]. This is particularly accurate for the construction industry [2][4-7]. As a result, prefabrication in construction is gradually being utilised across the world, predominantly in North America, Europe and Asia [5][7]. In Australia, modular construction industry is disproportionately valued at $4.5 billion, compared to the overall worth of $150 billion in the rest of the world [8]. While prefabrication is the process where parts are manufactured off-site, modular construction on the other hand, involves the utilisation of parts along with their installation to form a complete structure such as a building.

Regardless of all the benefits of prefabrication, conventional construction is still commonly used in high-rise construction due to the uncertainties and misconceptions generated by prefabrication [4][6] [9][10]. According to [10], some of the reservations in regard to adopting prefabrication are those related to the design, the transportation, as well as the installation processes. Nonetheless, [10] highlighted that, in general the advantages of using modular prefabrication in construction outweighs their drawbacks. Accordingly, this paper will review five case studies to further compare and highlight the advantages and disadvantages of modular prefabrication.

2. Literature review
Prefabrication is a process where parts of the building such as walls, facades, partitions and so on are manufactured off-site-factory environment, and delivered to the construction site for assembly [9][11-13]. Modular construction can also resemble manufacturing process, where for example room-size
volumetric units are mass-produced [14][15]. As previously mentioned, the majority of unit elements in prefabrication are designed and built off-site under controlled plant conditions. Such manufacturing conditions have the tendency to induce significant cost and result in time saving, as well as improved quality and waste minimization [8], [16-20]. Overall, modular prefabrication can be viewed as the basis; fire-resistance, low maintenance, designability, buildability etc. construction technique [10]. Figure 1 shows a typical module framing schematics.

Figure 1. Typical module framing (CTBUH, 2013).

As shown in figure 1, each module has its own cage of welded tube steel, allowing more structural materials to be added than conventionally framed light-gauge projects. The advantages of such simple yet efficient building systems include rapid time and reduced project cost. Although, modular prefabrication has such advantages, nonetheless, some of the main remaining and on-going uncertainties include the lack of market demand and public perception of off-site fabrication. These uncertainties along with the ease of transportation and longevity raise numerous concerns [17-20]. For instance, private companies need to be assured of long-term market demand for modular prefabrication due to the substantial cost that might occur from constructing a factory off-site [21-25]. Other key challenges include high transport costs and long distances to markets, as well as damages during transportation, etc. [26-27]. In this regard, [28], and [29] explained that modular prefabrication's acceptance is due to the lack of governmental involvement and impact on the building regulations. This is particularly true for the Australian industry. Therefore, further studies need to be undertaken to highlight the analysis and discoveries of modular prefabrication.

3. Research methodology
Results from mixed methods of quantitative and qualitative research have been presented in this paper. Five case studies have been reviewed to further highlight some of the analysis and discoveries related to modular prefabrication. The data was sourced from available publications and then compared and analysed. The overall finding was then evaluated and presented.

4. Case studies
A brief overview of the five case studies is presented in table 1.

| Case study | Location | Elevation | Duration | Purpose |
|------------|----------|-----------|----------|---------|
| United States | 461 Dean Street, Brooklyn, New York. | 32 Storey | 48 months (2013-2016) | A residential tower comprising of 363 apartments. 50% of the apartments have been designated for low-, moderate- and middle-income New Yorkers. |
| Australia | La Trobe Tower 327 La Trobe St, Melbourne, Victoria. | 43 Storey | 19 months (2015-2016) | A residential tower comprising of 206 luxury one and two bedroom apartments. |
| China | SkyTower 357 Brisbane Road, Chermside, Brisbane. | 57 Storey | 12 months (2013-2015) | A multi-purpose building comprising of 19 stories, 809 apartments and office spaces for up to 1,000 people. |
| Australia | Schofields Apartments 33-35 Wood Street, Darwin, Northern Territory. | 29 Storey | 21 months (2012-2014) | It is a hotel and residential tower that incorporates 25 modular floors built on an 8 level podium structure. |
| United Kingdom | Victoria Hall Student Accommodation 1 Cowell Street, Wolverhampton. | 25 Storey | 15 months (2008-2009) | It is a purpose-built modern complex comprising of 363 individual modules. |
As noticed, the selected five case studies are comparable in terms of number of levels and duration. This was the main reason to select these five case studies. Unfortunately, due to intellectual property rights, data related to project cost could not be shared. However, in this instance it is safe to assume that the costs of the five structures were also similar. A cross-case analysis was performed to further examine those five buildings, and the results were presented in Table 2.

Table 2. Cross analysis of the case studies.

| Case study | Prefabrication % | Types of Conventional Construction | Types of Prefabricated Construction | Design Techniques | Completion rate |
|------------|------------------|------------------------------------|-------------------------------------|------------------|-----------------|
| 1          | 60%              | • First floor and a podium structure comprising of 4 floors | • Whole apartment prefabricated modules • Pre-fitted interior finishes, cabinets & furniture • Pre-fitted pipes & ducts • Building Structure (steel) • Building facade • Floor section • Bathroom pods • Windows | Modular Construction: the core method • Load-bearing columns | 1 floor per week |
| 2          | 30%              | • Up to level 2 of the building • Interior fit-outs | • Whole apartment prefabricated modules • Pre-fitted interior finishes, cabinets & furniture • Pre-fitted air ducts and pipes • Building Structure (concrete) • Building facade • Floor section • Bathroom pods • Windows | Modular Construction, interlocking facade system and bathroom pods • Load-bearing columns | 2 floors per week |
| 3          | 90%              | • Interior fit-outs | • Pre-fitted air ducts • Building structure (steel) • Building facade • Floor section • Pre-installed components • Windows | Modular Construction: the core method • Load-bearing columns | First Phase: 20 floors per week Second Phase: 19 floors per week |
| 4          | 70%              | • Podium structure comprising of basement and 8 floors • Interior fit-outs | • Whole apartment prefabricated modules • Pre-fitted interior finishes, cabinets & furniture • Pre-fitted pipes & ducts • Building Structure (steel) • Building Structure (concrete) • Building facade • Floor section • Bathroom pods • Windows | Modular Construction: the core method • Load-bearing columns | 1 floor per week |
| 5          | 90%              | • Ground floor with in-situ concrete • Interior fit-outs | • Whole apartment prefabricated modules • Pre-fitted interior finishes, cabinets & furniture • Pre-fitted pipes & ducts • Building Structure (concrete) • Building facade • Floor section • Bathroom pods • Windows | Modular Construction: the core method • Load-bearing columns | 1 floor per week |

It can also be noticed that the five structures have many other similarities ranging from percentage of prefabrication to completion rate. Adopting more prefabrication construction will generally increase the speed and reduce duration during construction. Apartment modules commonly comprise pre-installed windows, walls, ceilings and so on. This method of manufacturing whole-apartment modules off-site has trended over the years as the earliest modular project started in 2008. From 2008 till now, fully completed modules are still being utilised in high-rise construction projects.

The modules in case studies 1, 2, 4 and 5 were all installed in similar ways. The modules were lifted into place by a crane and bolted together by a team of riggers. In case study 3, off-site production was used in a unique way by manufacturing steel components to size and delivering to the construction site in flat packs. Further, the modules were not delivered as a whole-apartment unit.
Floor modules were delivered with steel components, which were bolted and welded together on-site as whole-apartment modules. On the other hand case studies 1, 2, 4 and 5 were completed approximately within the same duration, whilst case study 3 took the least amount of time to be completed. A closer investigation determined that, the project organisers for this case study utilised AMT which in turn utilised more rapid manufacturing process.

5. Findings
Although four out of the five case studies manufactured whole-apartment modules off-site, different components were used to make the floor section of the modules. The floor section across the five case studies differentiated in terms of their use of steel and concrete. Case studies 1 and 3 used steel for their flooring, whereas, case studies 2, 4 and 5 used concrete floor slabs. On the other hand, case studies 1 and 4 adopted the same technique of using lightweight concrete floor slabs to allow the modules to be stacked on top of one and another. Case study 5 also comprised of a concrete floor, however, a 150mm deep PFC steel section was used. Although generally, the five case studies were successful, there were some complexities which are summarized in table 3.

Table 3. Summary of the complexities.

| Case study | Specific assembly requirements | Complexities |
|------------|--------------------------------|--------------|
| 1          | Finished modules are transported on-site. On-site modules are then bolted together and connection points are tied. | Additional lifting hooks were required due to faulty existing ones. |
| 2          | Completed prefabricated units are delivered on-site. On-site the units are then lifted into place by a crane and locked together by a team of riggers. | Some small panels were damaged during the transportation. |
| 3          | Modules are completely built in Ningbo, China and transported to the construction site. On-site the modules were lifted into the right position by a crane and bolted together. | Problems with some modular locking due to alignment issues. |
| 4          | Floor/ceiling modules are delivered on-site and assembled using a special construction method. On-site, the workers then lift the boards, tighten the bolts and conduct painting. | Panels damaged due to lifting via cranes and over tightening. |
| 5          | Finished modules are transported on-site. On-site modules are bolted together and connection points are tied. | Delay in modular deliver due to large modules being transported slowly. |

Overall, the module framing across the five case studies were similar in terms of materials used for the structural frame of the modules. Steel was used in all five case studies, however case study 4 consisted of a combination of steel and concrete in the structural frame. For this structure, concrete was poured in-situ into the steel columns to create concrete columns. The technique of bracing varied across projects as brace frame was used in case studies 1 and 4. While cross bracing was used in case studies 2 and 5, and diagonal bracing was used for case study 3. However, the common factors in all 5 projects was the use of steel frame and load bearing columns. Further analysis would perhaps focus on the specific assembly requirements of each project.

6. Conclusion and recommendations
The aim of this paper was to compare case studies in prefabrication including modular construction. Subsequently, this paper reviewed five case studies around the globe. The comparison of these case studies demonstrated that China had the fastest construction rate by manufacturing steel modules off-site. This was presumably due to significant use of AMT. Such new technique can potentially be the next era of prefabrication construction in high-rise construction. Companies which are contemplating the adoption of modular prefabrication should utilise AMT to enhance the design technique and assembly of prefabricated flat packs.

Nonetheless, due to the limitations of research and applicability of collecting data, further research into the costing of each project can be undertaken to complement this research. The estimated project
budget and actual cost were not available to the public; therefore a strong comparison could not be made between the projects. During this research, it was understood that case study 3 was built with the shortest project duration. However, further details into the costing, number of workers and number of hours involved in the process could be evaluated. Although, some of the case studies may have been completed in half of the time compared to others; the project cost may have been more than double. Consequently, to effectively compare projects, all aspects involved in those projects need to be assessed in order to determine the actual project success.

**Data availability statement**

Some or all data, models, or code generated or used during the study are available from the corresponding author by request.

**References**

[1] Akadiri, O., (2015), "Understanding barriers affecting the selection of sustainable materials in building projects", Journal of Building Engineering, vol. 4, pp. 86-93, Elsevier.

[2] Baer, D., (2015), 'A simple design innovation let a Chinese entrepreneur build a 57-story skyscraper in 19 days', Business Insider Australia.

[3] Bock, T., (2015), ‘The future of construction automation: Technological disruption and the upcoming ubiquity of robotics,’ Automation in Construction, vol.59, pp. 113-121.

[4] Carrerker, M., and Langar, S., (2014), ‘Factors Affecting Large Scale Modular Construction Projects’, 50th ASC Annual International Conference Proceedings.

[5] Council on Tall Buildings and Urban Habitat (2013), ‘Atlantic Yards B2 – Modular on the Rise’, Council on Tall Buildings and Urban Habitat.

[6] De Luca, A., Chen, L., and Gharehbaghi, K., (2021), ‘Sustainable utilization of recycled aggregates: robust construction and demolition waste reduction strategies’, International Journal of Building Pathology and Adoption, in press.

[7] Gardiner, P., (2015), ‘The Construction of a High-Rise Development Using Volumetric Modular Methodology’, Council on Tall Buildings and Urban Habitat, Conference proceeding, pp. 136-143.

[8] Gharehbaghi, K. and Scott-Young, C., (2018a), "GIS as a vital tool for Environmental Impact Assessment and Mitigation", Earth and Environmental Science, Institute of Physics, United Kingdom, vol. 127, no. 1, pp. 52-57.

[9] Gharehbaghi, K. and Scott-Young, C., (2018b), "Waste diminution in construction projects: Environmental predicaments", Earth and Environmental Science, Institute of Physics, United Kingdom, vol. 127, no. 1, pp. 58-63.

[10] Gharehbaghi, K., (2015), "Advancements in concrete technology in Australia: geo-polymer concrete", International Journal of Constructed Environment, Volume 7, issue 1, pp 19-29.

[11] Gharehbaghi, K., (2017), “Modular High-rise Construction as an alternative Building System”, International Journal of the Constructed Environment, 8(3), pp 15-25.

[12] Gharehbaghi, K., and Chenery, R., (2017), "Fiber Reinforced Concrete (FRC) for High Rise Construction: Case Studies", Materials Science and Engineering, vol. 272, pp 223-229.

[13] Gharehbaghi, K., and Georgy, M., (2019), "Sustainable Construction by Means of Improved Material Selection Process", International journal on the Academic Research Community publication, Volume 1, issue 1, pp 85-94.

[14] Gharehbaghi, K., and Rahmani, F., (2018), "Practicalities and Developments of High-Rise Composite Structures: Case Studies", Materials and Technologies in Engineering, pp 153-159.

[15] Gharehbaghi, K., Georgy, M., and Rahmani, F., (2018), "Composite High-Rise Structures: Structural Health Monitoring (SHM) and Case Studies", Materials and Technologies in Engineering, pp 146-152.

[16] Giesekam, J., Barrett, J., Talyor, P., (2015), "Construction sector views on low carbon building
materials”, Building Research & Information, vol 44, pp. 423-444.

[17] Isaac, S., Bock, T. and Stoliar, Y., (2016), ‘A methodology for the optimal modularization of building designs,’ Automation in Construction, vol. 65, pp. 116-124.

[18] Jahan, A., Edwards, L., and Bahraminasab, M., (2016), "The importance of decision support in materials selection", Multi-criteria Decision Analysis for Supporting the Selection of Engineering Materials in Product Design, pp. 1-23, Elsevier.

[19] Lockrey, S., Verghese, K., Crossin, E., and Nguyen, H., (2018), "Concrete recycling life cycle flows and performance from construction and demolition waste in Hanoi", Journal of Cleaner Production, vol. 179, pp. 593-604.

[20] Marsono, K., Ying, J., Tap, M., Chieh, C., and Haddadi, A., (2015), 'Standard Verification Test for Industrialised Building System (IBS) Repetitive Manufacturing,’ Procedia CIRP, vol.26, pp. 252-257.

[21] Vaha, P., Heikkila, T., Kilpelainen, P., Jarviluoma, M., and Gambao, E., (2013), ‘Extending automation of building construction – Survey on potential sensor technologies and robotic applications,’ Automation in Construction, vol.36, pp. 168-178.

[22] Volner, I., (2014), ‘Updated: Construction Stops on the B2 BKLYN High-Rise at Atlantic Yards’, The Journal of the American Institute of Architects.

[23] Wong, P., Owczarek, A., Murison, M., Kefalianos, Z., Spinozzi, J., (2013), "Driving construction contractors to adopt carbon reduction strategies - an Australian approach", Journal of Environmental Planning and Management, vol. 57, no. 10, pp. 1465-1483.

[24] Xua, J., Fleiterb, T., Eichhammerb, W., Fana, Y., (2012), "Energy consumption and CO2 emissions in China's cement industry: A perspective from LMDI decomposition analysis", Vol. 50, pp. 821-832.

[25] Zhai, Y., Zhong, Y., and Huang, Q., (2015), ‘Towards Operational Hedging for Logistics Uncertainty Management in Prefabrication Construction,’ IFAC-PapersOnLine, vol.48-3, pp.1128-1133.