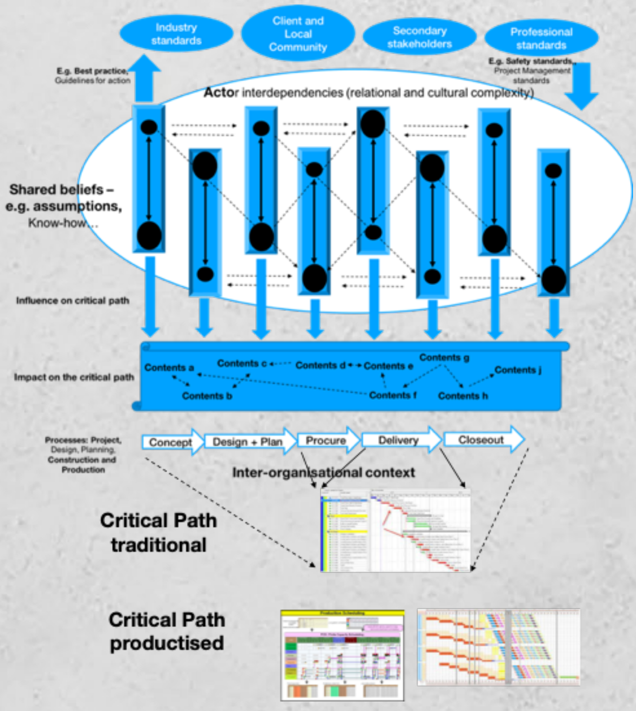
CRC#30: CRITICAL IMPACT THROUGH PRODUCTISATION

FINAL REPORT – FOR PUBLIC



EXECUTIVE SUMMARY CONTENTS

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Date of this report:	31/03/2023
Project completion date:	31/01/2023
Program Leader reviewer:	Duncan Maxwell, Chris Knapp
Project Title:	CRC#30 Critical Path Impact Through Productisation
Project Duration:	1 Year 4 Months
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Acknowledgements:	The project team would like to acknowledge our industry partner liaisons Karl-Heinz Weiss and Steven Huang for their contribution to this project. Thank you to the interviewees who participated anonymously in the study.

EXECUTIVE SUMMARY

This report investigates the scheduling benefits and challenges of prefabricated construction in medium-rise timber buildings, specifically focusing on the critical path impact of productisation. The study explores various aspects of modular construction, productised risk, dynamic scheduling and systems integration in productised building projects.

- Key benefits of modular construction include accelerated construction time, improved installation cycles and favourable comparisons with conventional methods. However, challenges arise in areas such as site preparation, assembly, design-related issues and logistics. Despite these challenges, comprehensive planning, flexibility and coordination are crucial to achieving schedule benefits in prefabricated construction projects.
- Productisation in construction presents risks, but also offers potential time savings and increased project complexity. To fully leverage the benefits of off-site construction, the report recommends adopting a design for manufacture and assembly (DfMA) approach, early involvement of project parties and a system dynamics approach to risks based on product typology.
- The case studies analysed in this report demonstrate the advantages and disadvantages of a productised approach in mass timber building projects. Proper implementation of DfMA and quality management processes can lead to significant benefits, but further research is needed to explore decision making in such projects.
- Dynamic scheduling is a process used to mitigate disruptions in the building delivery, providing control and flexibility for project teams. The construction industry has made progress in implementing point solutions for scheduling and progress monitoring, but a more integrated approach is needed to enable better resource utilisation and efficiency.
- The report also reviews construction project management and scheduling software, focusing on productisation capabilities. Factors to consider when selecting project management information systems (PMIS) include required features, performance, implementation time, vendor support and compatibility with the organisation's supply chain partners.
- Finally, systems integration in productised building projects is essential for project success. The report identifies key areas for improvement, such as early consultation with clients on productisation options, incorporating construction feedback and lessons learned, and developing in-house productisation capabilities. A roadmap is provided to align with industry best practices, with recommendations for both long-term and short-term goals.

In conclusion, the report highlights the importance of addressing technical and process barriers to fully capitalise on the benefits of modular construction and productisation in medium-rise timber buildings. By overcoming these challenges, the construction industry can increase efficiency, reduce waste and improve quality in building projects.

PROJECT OVERVIEW

This report summarises the research project *CRC#30 Critical Path Impact Through Productisation*.

Background

In recent years, industrialised processes have led to increased attention towards alternative construction methods, with prefabrication emerging as a promising solution to the construction industry's challenges.

Prefabrication offers numerous advantages over conventional construction, such as improved predictability of project delivery time, reduced construction time, enhanced productivity, higher product quality, lower on-site workforce demand, better working conditions, reduced accident rates, noise and dust reduction, diminished material and resource waste, superior environmental performance and decreased project costs. Despite these benefits, the uptake of prefabricated construction remains limited. In Australia in 2022, off-site construction accounted for only 3% to 5% of the approximately $150 billion construction market, even with the government's investment in prefabricated infrastructure projects.

A key obstacle to the widespread adoption of innovative off-site techniques is the difficulty in ensuring and understanding their benefits. Many construction industry practitioners lack a clear understanding of the advantages of prefabrication, leading to decision making based on unsubstantiated evidence and personal preference rather than reliable information. A solid and organised knowledge base, alongside guidelines for prefabricated constructions, can be established through extensive studies based on real-world project experiences.

Industry problem

In the construction industry, the critical path method is an essential tool for decision making and comparison of productivity and performance management. This method helps coordinate construction planning and execution, defining task prioritisation and interdependence. However, the introduction of new production modes and planning arrangements, such as manufactured components and off-site prefabrication, has only partially delivered the promised productivity gains and performance improvements. In the Australian context, the impact of these alternative modes on project planning and on-site delivery of high-rise buildings remains underexplored.

Aim and objective

Building 4.0 CRC Project #30 aims to investigate how delivery diversions and multivariant impacts affect the critical path for medium-rise buildings during on-site delivery. The project will examine roadblocks to the effective implementation of a productised building approach, focusing on its potential impact on transforming building programs to establish the context and conditions for future project timelines.

This scoping study seeks to map the critical path impact that can be harnessed by employing a unified productised building approach perspective during construction, in line with the productivity gains envisioned by Building 4.0

Research team

The CRC#30 research team comprised experts from:

- the Future Building Initiative (FBI), Art, Design and Architecture, and the Faculty of Engineering at Monash University (MU)
- the Department of Infrastructure Engineering at the University of Melbourne (UoM).

Research approach

The multifaceted research approach included:

- Literature review: The existing literature is examined to investigate the scheduling benefits and challenges associated with prefabricated construction in medium-rise timber buildings, specifically focusing on the critical path impact of productisation (Chapter 1). The review explores various aspects of modular construction, including productised risk (Chapter 2), dynamic scheduling (Chapter 4), and systems integration within productised building projects (Chapter 6).
- PERT - Risk analysis: Quantification and critical path evaluation for different project delivery stages of productised building approach. The critical path for the project simulation is based on the Fenner Hall building report at the Kambri ANU Acton campus, provided by Lendlease. Quantitative risk assessments are conducted on 4 hypothetical buildings with varying degrees of productisation. The risk scores and project durations, along with confidence intervals for completion times, are generated using PERT. Multiple Critical Path analysis based on the level of productisation and hybrid adoption provide a risk score (Chapter 2).
- The Case study analysis: The case study analysis investigated 6 projects to better understand the potential of a productised approach in building delivery. The selected buildings include Forté Living (Melbourne, Australia), Brock Commons Tallwood House (Vancouver, Canada), Fenner Hall (Canberra, Australia), International House (Sydney, Australia), 25 King St (Brisbane, Australia) and Daramu House (Sydney, Australia). Interviews with project team members were conducted for some projects (Forté, Fenner Hall, and 25 King St) in a semi-structured format, guided by a list of questions but allowing for organic conversation. For the remaining projects, analysis relied on project materials provided by stakeholders and available online. The analysis aimed to determine the degree of productisation, drivers, successes, challenges and risks associated with each case study project (Chapter 3).
- Market review: The dynamic scheduling software market was analysed by reviewing 96 solutions, including project and construction management software and other related solutions. Based on exclusion criteria, 7 software with productisation capabilities, 16 project management software programs, an aPaaS for construction, and a scheduling enhancer solution were shortlisted. Dassault Systemes and Autodesk received the highest ratings in modularity, interoperability, functionality and customisation. The market research involved a literature review, examining relevant terms through Google search, review websites and social media sources, particularly LinkedIn. We generated a comprehensive list of potential solutions and analysed vendor websites for additional information to define a definitive list of software solutions (Chapter 5).
- Process Roadmap: We employed process theory to understand Lendlease's internal processes, key considerations, stakeholders and deliverables for each lifecycle stage. The project team prepared a roadmap for Lendlease that summarised gap analysis findings, provided a general description of project processes, highlighted best practices and outlined project management tools and techniques. However, this information is commercial-in-confidence, so is not included in this report.
- Practical emphasis was maintained through biweekly discussions with industry partner liaisons, Karl-Heinz Weiss and Steven Huang, ensuring organisational knowledge and experiences were incorporated and reflected.

PROJECT FINDINGS AND OUTCOMES

Findings and outcomes – Chapter 1 Investigating scheduling benefits and challenges of prefabricated construction context

This chapter highlights the perceived benefits of modular construction, including accelerated construction time, potential for improved installation cycles and favourable comparisons with conventional methods.

- The literature review recognises the potential of time savings and other benefits through concurrent off-site and on-site work, controlled manufacturing environment, standarisation and precision, pre-installed systems and finishes, efficient assembly process, improved logistics and planning, and reduced on-site labour requirements.
- Modular construction presents unique challenges and requirements for site preparation, assembly and the on-site team. Adaptability, specialised knowledge, effective communication and coordination are critical to successfully delivering a modular construction project.
- Many modular components come with pre-installed systems (such as plumbing, electrical and HVAC) and finishes (such as flooring, walls and ceilings).
- Many building projects deploy a hybrid of modular construction and traditional delivery, which requires a specialised workforce with expertise in off-site manufacturing, assembly and coordination to support traditional trades, and tampers the full potential as risks increases with the interfaces and several benefits are lost.

The case study context provides several key lessons in terms of schedule benefits, flexibility, modularisation, dependencies and challenges in implementing prefabricated construction projects:

- Comprehensive and detailed planning, visual planning and daily updates help ensure a streamlined assembly process and minimise delays. Despite uncertainties and setbacks, the project was completed with only a 15-day delay.
- The project management team demonstrated flexibility by adjusting working hours, increasing the workforce and resources, and coordinating daily with the installation team to recover lost time and maintain productivity.
- The use of prefabricated core modules enabled time savings, increased safety and improved buildability, leading to a cleaner, quieter and more sustainable construction site.
- Effective coordination among various project stakeholders, including suppliers, subcontractors and on-site crews, is critical for ensuring smooth project execution. Accurate design and efficient transportation and logistics are essential for timely project delivery.
- Design and logistics must be meticulously reviewed and planned to ensure success.

Findings and outcomes – Chapter 2 Productised risk

The chapter provides insights into the risks involved in productised construction management through literature review, market analysis, stakeholder interactions and case study analysis. The first part of the chapter summarises the findings of the literature review on the topics of hybrid project risk management. The second part introduces a system dynamics-based framework to analyse schedule delay risk in productised construction projects.

- The study found productisation in construction is rapidly advancing with increasing publications aimed at solving specific problems in the project value chain.

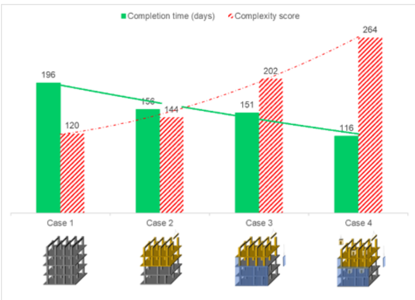

Figure 1: Productised complexity level

- The chapter highlights the sources of uncertainties and risks in different sub-sections of stakeholder management, change management, supply chain management, project scheduling and optimisation, product typologies in off-site manufacturing and manufacturing.
- The simulation analysis in the latter half of the chapter quantifies the sources of time risks in productised construction.
- The results showed potential time savings but also higher project complexity with increasing levels of productisation.
- To realise the benefits of off-site construction, the chapter recommends key steps such as a DfMA-led design, early involvement of project parties, consistent data formats, a lessons learned register, top-down planning with bottom-up last planner system, and a system dynamic approach to risks based on product typology.

Findings and outcomes – Chapter 3 Productisation case study

This case study analysed 6 mass timber building projects to understand the various ways that a productised approach to building delivery can be implemented, and the associated advantages and disadvantages.

- The study determined the type and extent of productisation used in each project, as well as the reasons for using a productised approach.
- The decision to adopt a productised approach was mainly driven by the benefits of mass timber as a building material and the potential for faster construction.
- The main successes of the productised mass timber approach included reduced labour, speed, safety and reduced need for scaffolding, as well as industry recognition.
- Challenges included managing design, manufacture and delivery quality, including environmental (weather) impacts, all of which are potential risks with a productized approach.
- Proper implementation of design for manufacture and assembly (DfMA) and quality management processes can provide significant benefits, and should be considered in planning processes.
- Further research is needed to verify the findings of this study, and to explore questions related to decision making in such projects.

Findings and Outcomes – Chapter 4 Dynamic scheduling

Dynamic scheduling (DS) is a process used to mitigate disruptions in the building delivery.

- DS provides delivery teams with desirable control and flexibility. It involves analysing real-time events, assessing the current status of the schedule and making optimised modifications to the schedule.
- The categorisation of DS is based on the strategy used to generate the schedule baseline and respond to real-time events.
- The construction industry has made significant progress in implementing point solutions for construction scheduling, progress monitoring and schedule adjustments. However, the fragmented nature of these solutions hinders the implementation of DS on construction sites.
- There is a demand for mapping as-planned and as-is data at the activity level to standardise the data structure and enable better resource utilisation and efficiency.
- An ontological model of the schedule can be created to extract data from different sources, including databases and paper-based documents, which will improve knowledge accumulation and duration/resource estimation for construction activities.

Findings and outcomes – Chapter 5 Market review: DS software

Project management information systems (PMIS) provide a centralised platform to monitor activities and progress in construction projects, with scheduling and tracking features essential for success. A variety of software solutions exist in the market, including work management tools, portfolio management, scheduling, analytics and project management software. Market research is necessary to compare and evaluate these products, as there are many vendors to choose from.

- The chapter provides an overview of construction project management and scheduling software, particularly those with productisation capabilities, to help organisations select the best PMIS for their needs.
- Factors to consider when selecting PMIS include required features, performance, implementation time, vendor support and compatibility with the organisation's supply chain partners.
- Key limitations of the research include inconsistent and biased data from vendor websites and variations in the number and date of user reviews.
- The research shortlisted 7 software with productisation capabilities, 16 project management software, an Application Platform as a Service (aPaaS) for construction, and a scheduling enhancer solution.

Findings and outcomes – Chapter 6 Systems integration in productised building projects: literature review

Systematic literature review

The building sector has recently seen a surge in new technologies and digitalisation, leading to the embracing of new levels of complexity. The growing market for productised building projects requires effective systems integration, which combines system elements or components to create a product or service. This chapter identifies 5 research clusters in this area: 1) Building Information Modelling (BIM) and Information Communication Technologies (ICTs); 2) Design and Interface Management; 3) Inter-organisational Projects and Innovation; 4) Collaboration and Modularity; and 5) Critical Success Factors (CSFs) and Manufacturing.

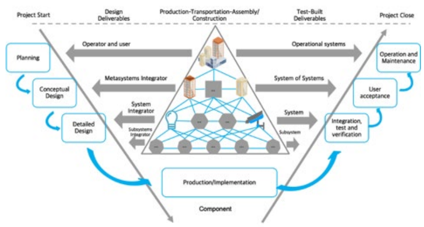

Figure 2: Project Lifecycle-based 'V' Model of Systems Integration

Key findings for systems integration in productised building projects include:

- Using BIM and ICTs requires maintaining an integrated repository for all building component workflows and information.
- Coupled or decoupled design supports collaboration by coordinating and cooperating within a modular or integral organisation.
- Systems integration in productised building projects promotes inter-organisational innovation.
- The 'V' model offers a framework for systems integration practices across various project phases.
- Emphasising critical success factors, such as robust design and early design freeze, close collaboration, effective communication and early stakeholder engagement, is essential for project success.

Further, modularity and integration play key roles in achieving collaboration throughout the productised building project lifecycle. The characteristics of different systems integrators and their roles in supporting collaboration are essential for success. Three recommended strategies include:

- creating a project-based learning platform
- implementing coupled and decoupled thinking in integration
- developing and sharing professional systems integration knowledge

FUTURE RESEARCH PLANS

Draft Outline Proposal Developed by: Ivana Kuzmanovska, Robert Moehler, Yihai Fang, Duncan Maxwell.

This project concludes by recommending further research under Project CRC#61, which will build on previous CRC projects and focus on productivity improvement in the construction industry.

The aim of Project CRC#61 is to provide insights into productivity improvement in the construction industry, focusing on data-informed decision making from product and process perspectives. This research will contribute to the development of practical strategies for waste reduction, efficiency improvements and increased effectiveness in construction projects.

Productisation risks and opportunities Chapter 2&3:

Call to map building systems and their interfaces across various building typologies, scales and markets to improve efficiency and quality, guided by waste reduction. The research activities include case studies, mapping constraints, interviews with decision makers and developing a data-led DfMA framework.

Dynamic scheduling application Chapter 4:

Call to create a standarised data structure for mapping as-planned and as-is data at the activity level, using an ontological model of schedule with 6 elements. The data will be curated from different sources and used to improve construction activities. This will be achieved through digital transformation and sensing technologies, which will generate and capture data for product and process design. The research activities will involve identifying key products and processes, constructing a data schema, proposing data capture methodologies, testing the approach in a pilot project, and developing a roadmap for enterprise-level implementation

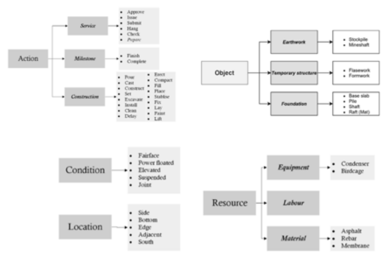

Figure 3: Elements for a construction activity in schedules [19]

Process application Chapter 6:

Call to evaluate construction business models that leverage data capture and sensing strategies to improve project planning, control and assessment. This approach is informed by Lean and DfMA recommendations and enables faster learning cycles and continuous improvement. Research activities include analysing business models, identifying new forms of collaboration, investigating management needs, analysing impact and developing a change roadmap.

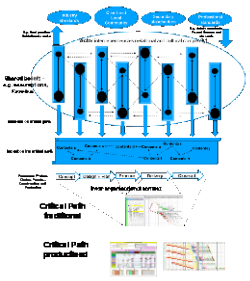

Figure 4: PLC decision path

CHAPTER 1 CONTENTS

CHAPTER 1: INVESTIGATING SCHEDULING BENEFITS AND CHALLENGES OF PREFABRICATED CONSTRUCTION: A CASE STUDY IN AUSTRALIA

Kaveh Mirzaei, Priyadarshini Das and Robert Moehler

This chapter delves into potential benefits and challenges of productisation with modular construction of buildings. The review establishes the claims and then compares lessons learnt from contemporary industry projects. Conceptual emphasis was grounded at fortnightly conversations with industry partner liaisons, Karl-Heinz Weiss and Steven Huang, to capture and reflect on organisational knowledge and experiences.

1.1 Background

The construction industry accounts for a large share of Australia's gross domestic product (GDP), with over 1.15 million construction workers involved. However, due to the current Covid-19 pandemic, this GDP contribution declined by approximately 8% in 2020 (GDP from Construction – Countries – List n.d.).

Adopting new approaches, including automated construction, virtual design and construction, and prefabricated or off-site construction, can boost productivity and be conducive to increased robustness of the construction industry to future crises (Gatheeshgar et al. 2021). Typically, buildings are constructed using on-site, traditional or conventional methods, referring to sequential construction at the permanent use location. There are several problems associated with conventional construction methods, such as extended construction periods, excessive waste production, subpar productivity, poor energy efficiency and low safety conditions (Guo, Goh and Le Xin Wong 2018; Mak et al. 2019; Razkenari et al. 2020).

Over the past few years, industrialised processes have impacted the building sector, causing academics and industry to give more attention to alternative construction methods. In view of this, prefabrication has been considered a viable and game-changing method to overcome the construction industry's challenges (Almashaqbeh and El-Rayes 2021; Goulding et al. 2014; Paliwal et al. 2021). Prefabricated or off-site construction refers to a process by which building components are produced in a manufacturing factory and then transported to the construction site for assembling and creating the final structure.

Off-site construction could be categorised into 4 levels based on the degree of implemented prefabrication:

1. component sub-assembly: small elements that are typically assembled off-site, such as doors
2. non-volumetric pre-assembly: pre-assembled units that do not enclose space, such as trusses
3. volumetric pre-assembly: pre-assembled units that enclose a useable space, but are not part of the building structure, such as bathrooms

4. complete (modular) construction: pre-assembled volumetric units which when combined could form a whole building (Goodier and Gibb 2007).

Moreover, timber has been used as a preferable construction material and a sustainable alternative to steel and concrete construction. However, timber-based buildings were initially limited to small and low-rise buildings due to several limitations, such as low fire and water resistance and variability of properties such as consistency, durability and strength. Engineered mass timber products are produced to address the limitations of typical timber elements by offering enhanced consistency, durability and strength. Cross-laminated timber (CLT) and glue-laminated timber (Glulam) are recent innovations that revolutionised timber structures. CLT is commonly composed of an uneven number of layers of timber boards, with adjacent layers glued together in an orthogonal configuration. Glulam comprises layers of wood that are placed parallel to each other and bonded together using durable and moisture-protected adhesives. Its structural strength allows it to be used as floor and roof decking, besides typical beams and columns. Engineered timber elements are often needed in significant sizes (typically 3–4 m wide and 10–20 m long) and must be produced in factories with automated machines and fabricated as finished building components. Therefore, prefabrication is a necessity rather than an option since massive components cannot be produced in the required size on the construction site.

Prefabrication has been seen as a game-changer and offers substantial advantages over conventional construction, including better predictability of project delivery time, reduced construction time, increased productivity, higher product quality, lower on-site workforce demand, better working conditions, lower accident rates, noise and dust reduction, reduced material and resource waste, better environmental performance and reduced project costs (Almashaqbeh and El-Rayes 2021; Ferdous et al. 2019; Godbole et al. 2018; R. Jiang et al. 2018; Y. Jiang et al. 2019; Kamali and Hewage 2016; Paliwal et al. 2021; Teng et al. 2018). In the past, the process of creating each building is similar to developing a prototype in a manufacturing section. Each has a unique design and suffers from inefficiencies of one-time custom design resulting in significant waste, non-transferable learnings, and low productivity (Industrialised Construction: Driving Value with Productisation & DfMA Innovation | Ideas | Bryden Wood n.d.). Adopting prefabrication and productised construction will lead to specialisation, value-chain control and integration with industrial-grade supply chains, increased consolidation, customer-centricity and branding, investment in technology, internationalisation and sustainability (The next normal in construction Executive summary 2020).

Nevertheless, the uptake of prefabricated construction is hindered despite its extensive benefits. In Australia, off-site construction accounts for only 3–5% of the approximately $150 billion construction market (Navaratnam et al. 2022) despite government efforts to invest in prefabricated infrastructure, including community centres, schools and underground metros (Navaratnam et al. 2022). One of the main constraints on widespread application of off-site techniques is the difficulty of ensuring its benefits. Many construction industry practitioners do not clearly understand the advantages of prefabrication, and often make decisions based on unsubstantiated evidence and personal preference instead of reliable information (Blismas and Wakefield 2009).

A wide range of studies has investigated the implementation of prefabricated construction. However, since the benefits and challenges of implementing prefabricated construction are substantially different for each case study, we need extensive studies based on real-world projects to establish a solid and organised knowledge base and provide guidelines for prefabricated constructions. The following sections summarise the benefits and challenges of prefabrication presented in the literature. Then, we investigate the advantages and barriers in Australia via a real-world case study.

1.2 Benefits of prefabrication

1.2.1 Schedule benefits

Modular construction, or prefabricated construction, streamlines the building process by manufacturing components off-site in a factory setting, reducing on-site construction time (Godbole et al. 2018). This efficiency is achieved through concurrent off-site and on-site activities and summarised construction processes. In modular construction, the design and planning phase requires greater precision, which may slightly increase the time needed but can reduce errors during construction. Materials and components are typically procured in bulk, leading to economies of scale and potentially shorter lead times. However, careful coordination is necessary between suppliers and the manufacturing facility. The off-site manufacturing process allows for simultaneous work on multiple components, reducing overall construction time. Factory-controlled environments can minimise delays due to weather or site conditions.

Transporting prefabricated modules to the construction site can be time consuming, but proper planning can minimise delays. Manufacturing can be underway while the site is prepared, reducing overall project duration. Assembling prefabricated modules is generally faster than conventional construction methods, because they are designed for quick installation. This can significantly reduce on-site construction time.

Recent case studies show modular construction can reduce construction time by approximately 50% compared with conventional methods (type 4 of off-site construction classification (Modular construction: From projects to products | McKinsey n.d.)).

Modular construction simplifies the building process and requires a less skilled workforce (Gibb and Isack 2010). Modular construction typically results in higher quality control standards due to the controlled manufacturing environment, leading to fewer defects and faster commissioning. Prefabrication has proven to be a valuable solution for projects with strict completion dates, because it offers better predictability compared with conventional construction methods.

Off-site manufacturing allows for parallel work, minimising interruptions and enhancing productivity (Lu 2009). Further, a consistent workforce, reduced time between trades, better supervision, and an organised workflow contribute to increased productivity and shorter construction times (Jaillon 2009). The risk of time extensions due to theft and weather conditions also diminishes (Kamali and Hewage 2016).

In summary, modular construction can significantly reduce project duration due to parallel workstreams, improved efficiency, and faster assembly times. However, it is essential to manage the design, planning, procurement, and logistics aspects of the project carefully to fully realise these time-saving benefits.

1.2.2 Economic benefits

Prefabricated construction can reduce costs and increase efficiency compared with conventional methods due to several factors. Prefabrication decreases the need for on-site workers, which can reduce congestion, increase productivity and reduce lower labour costs (Haas et al. 2000).

Simultaneous off-site manufacturing and on-site preparation can significantly reduce overall project timelines, leading to decreased finance costs and quicker returns on investment. Enhanced material management, standard designs, and factory production result in more efficient use of resources and less waste (Kamali and Hewage 2016). This contributes to overall cost savings.

Using standardised designs and controlled manufacturing processes allows for more accurate cost estimates, reducing the likelihood of cost overruns and budgetary surprises. Manufacturing building components in a controlled environment allows for improved quality control, which can reduce defects and rework. This leads to lower costs associated with repairs, maintenance, and warranty claims. Prefabrication can result in lower overhead costs, decreased risk of delays, and a more efficient installation process (Haas et al. 2000).

Prefabricated construction minimises delays due to adverse weather conditions and results in less site disruption, noise, and waste. This leads to lower costs associated with site management, clean-up, and potential fines or penalties. Reduced construction times can lead to lower financing costs, because loan durations are shorter. Additionally, quicker project completion can result in earlier revenue generation, offsetting finance costs. However, prefabricated construction requires meticulous planning and effective management to avoid extra costs (Zhang et al. 2018). By carefully managing design, planning, procurement, and logistics, prefabricated construction can offer significant economic benefits compared with conventional methods.

1.2.3 Safety and sustainability benefits

Prefabricated construction offers numerous safety and sustainability benefits compared with conventional construction methods, making it an appealing choice for projects prioritising safety and environmental responsibility.

By transferring a significant portion of work to the controlled environment of off-site factories, modular construction reduces the need for on-site labour and results in approximately 80% fewer accidents compared with conventional methods (Construction 2011; Haas et al. 2000; H. X. Li et al. 2013). This is due to factors such as reduced high-risk activities, severe weather exposure, congestion, and work during night-time accidents.

Factory production allows for more efficient use of materials and generates less waste. The construction process is more sustainable, because less material is discarded and sent to landfills (Kamali and Hewage 2016). Additionally, building elements can be dismantled and reused in other buildings at the end of their lifecycle (X. X. Li and Li 2013). Prefabricated components are often manufactured with higher precision, resulting in tighter seals and better insulation. This can improve energy efficiency in the completed building, reducing energy consumption and associated greenhouse gas emissions. Modular construction allows for more efficient resource use, such as water and energy, during the manufacturing process, which can lower environmental impacts and reduce overall ecological footprint.

Modular construction also results in less site disruption, dust, and noise compared with on-site construction (Digiovanni, Jeng, and Wan 2012; Jeng, Digiovanni, and Wan 2011). Prefabricated components are often made from low-VOC (volatile organic compound) materials, which can improve indoor air quality and contribute to a healthier living or working environment. This helps minimise the impact on local ecosystems and nearby communities. Modular buildings can be easily disassembled, relocated, or repurposed, promoting a more sustainable approach to building use and reducing the need for new construction materials. Modular construction often incorporates green building materials, such as sustainably sourced wood, recycled metals, and low-VOC paints and adhesives. This contributes to a more eco-friendly building and reduces environmental impact. A recent study that compared the life cycle costs of 2 student high-rise residential buildings with similar designs but different structures (one has a hybrid mass-timber structure while the other one has a traditional concrete structure) showed the timber structure has 25% less global warming potential and 18% less fuel depletion potential impacts compared with the conventional concrete structure (Teshnizi et al. 2018).

1.2.4 Quality benefits

The quality benefits of modular construction can improve performance, durability, and overall satisfaction for end-users. Building components are manufactured in controlled factory environments with standardised quality control measures, resulting in consistent and higher quality outputs than conventional construction sites, where environmental factors and varying workmanship can lead to inconsistencies (Teng et al. 2018). Advanced design and manufacturing techniques enable precise engineering of components. This precision ensures a better fit and finish in the completed building, reducing the likelihood of defects and leaks. In turn, this can lower costs associated with repairs and maintenance (Kamali and Hewage 2016) and warranty claims, and increase overall satisfaction for end-users. Further, prefabricated components often have tighter seals and better insulation, improving energy efficiency, reducing energy consumption, and increasing comfort for occupants.

Prefabricated modules are characterised by less variation in quality, high load bearing and strength, durability, lightweight structure, and high-quality finish. Moreover, because the module should have enough strength and load-bearing standards when transported by trucks, high-quality materials that are durable, lightweight, and resistant to weather are required. While modular construction often utilises standardised designs and components, it can also accommodate customisation and flexibility to meet specific end-user requirements, resulting in a higher quality end product tailored to individual needs (Gao and Tian 2020).

1.3 Challenges of prefabrication

1.3.1 Cultural and industry barriers

The widespread adoption of modular construction faces several cultural and industry barriers, including resistance to change, lack of awareness and understanding, limited skilled workforce, and regulatory challenges. The critical factors hindering the diffusion of prefabrication include unfamiliarity of most clients with its benefits and a pessimistic attitude towards this method (Mao et al. 2013). The construction sector has generally been slow to adopt new technologies and methods, which has led to a resistance to change and difficulties in embracing modular construction (Rahman 2013).

Many industry professionals may not fully understand the process, advantages, or potential of modular construction, and this lack of awareness can act as a barrier to adoption (Kamali and Hewage 2016). Further, adopting innovative prefabrication methods can be disruptive and require substantial changes to established practices, leading to concerns about role descriptions and identities in the work environment (Ruparathna and Hewage 2015).

Modular construction requires a specialised workforce with expertise in off-site manufacturing, assembly, and coordination (Wuni and Shen 2019). Labour unions are pursuing new laws and legislation to protect workers against job losses associated with adopting prefabrication (Polat 2008), limiting the development of prefabricated construction (Chiang, Hon-Wan Chan, and Ka-Leung Lok 2006). A lack of skilled professionals can hinder the growth of modular construction. Additionally, the construction industry often relies on a fragmented supply chain, posing challenges for modular construction projects that need a more coordinated and integrated approach to procurement, manufacturing, and logistics (Gan, Chang, and Wen 2018; Luo et al. 2015).

Building codes, regulations, and permitting processes, often designed for conventional construction methods, can sometimes create challenges for modular construction projects. Most construction professionals do not fully understand the business model of prefabricated construction. Therefore, decisions about using prefabrication are based on personal preference (Chen, Okudan, and Riley 2010). Lenders, investors, and insurance companies may perceive modular construction projects as higher risk due to unfamiliarity or concerns about long-term durability and resale value.

To overcome these barriers, it is essential to promote awareness and education about the benefits and potential of modular construction, invest in workforce training and development, and work with regulators and other stakeholders to address concerns and create a supportive environment.

1.3.2 Knowledge and experience barriers

Significant knowledge, skills, specialisation, and experience barriers can impede the widespread adoption of modular construction. The construction industry may lack sufficient training and education programs focused on modular construction techniques, creating a barrier to entry for professionals interested in transitioning to this method and hindering the development of a skilled workforce. Higher education institutions do not typically cover prefabricated construction, so many professionals have limited knowledge about the process and its potential benefits (Gan, Chang, and Wen 2018).

Modular construction requires specialised skills and expertise that are distinct from conventional construction methods. The construction industry traditionally consists of generalists who are familiar with various aspects of on-site construction. Modular construction, on the other hand, requires specialists in design, manufacturing, and assembly, logistics, and project coordination. A shortage of skilled workers with the necessary expertise can create a bottleneck in the growth of modular construction, (Zhang et al. 2018).

Because modular construction is a relatively new approach, many professionals may lack experience working on such projects. This limited experience can create apprehension or resistance to adopting modular construction, hinder collaboration among project stakeholders, and increase the risks of change orders, schedule delays, and cost overruns (Gao and Tian 2020). The lack of standards and guidelines for designing and implementing prefabricated construction (including architectural, safety, acoustics, fire, and structural aspects) further adds to knowledge barriers (Zhang et al. 2018). Professionals in the construction industry may be hesitant to adopt new methods and technologies due to concerns about job security, changes to established practices, or fear of the unknown (Chiang, Hon-Wan Chan, and Ka-Leung Lok 2006).

Overcoming these barriers requires investment in education and training programs that focus on modular construction techniques, raise awareness about its benefits and potential, develop standards and guidelines, and encourage collaboration among industry stakeholders. By addressing these barriers, the construction industry can foster a skilled and experienced workforce capable of embracing modular construction methods and driving the industry forward.

1.3.3 Process and technical barriers

Prefabricated construction is substantially different from conventional methods and requires a comprehensive preliminary and detailed study before initiating the project. Modular construction often requires designs that can be broken down into standardised modules, which might pose challenges when working with complex or highly customised projects. Although prefabricated and typical buildings are subject to the same regulation in some respects, such as structural codes, the complexity of designing modules, connections, lifting, and assembly requires extensive knowledge and experience (O'Connor, O'Brien, and Choi 2016).

Integrating modular components with on-site construction elements can be challenging, especially when dealing with existing structures or incorporating non-modular elements into a project. Scope of work and component specification must be designed accurately before the production phase since modifying elements during construction is extremely hard and leads to cost overruns and time delays (Lara Jaillon and Poon 2010). Besides, complex design requirements of prefabricated buildings coupled with limitations of manufacturing plants could lead limit architectural innovations and adversely impact aesthetic aspects.

Modular construction may rely on specific materials or components that are not readily available or compatible with conventional construction methods, posing a challenge for procurement and supply chain management. Some modular construction systems may have limitations in terms of structural capacity, potentially restricting building height or span and affecting project feasibility (Gan, Chang, and Wen 2018).

Additionally, successfully executing prefabricated design requires integrated workflow involving different stakeholders in all phases of the project delivery process, including design, transportation, lift, and assembly. Moving large prefabricated modules from the factory to the construction site can be logistically complex, requiring specialised equipment, permits, and potentially affecting local infrastructure. Navigating these processes can be more complicated and time-consuming. Contractors, suppliers, designers, and owners should establish effective communication and coordination to provide necessary information for different parties throughout the project (Gan, Chang, and Wen 2018; Hwang, Shan, and Looi 2018).

By overcoming these challenges, the industry can capitalise on the benefits of modular construction, such as increased efficiency, reduced waste, and improved quality.

1.3.4 Logistical and transportation barriers

Logistical, transportation, and storage barriers play a significant role in modular construction, which involves moving prefabricated components from manufacturing facilities to construction sites and handling them efficiently (O'Connor, O'Brien, and Choi 2016).

Prefabricated modules can be large and heavy, requiring specialised transportation equipment such as oversized trucks, trailers, or cranes. Navigating size and weight restrictions on roads or bridges can be challenging, necessitating route planning to avoid potential obstacles. Transporting oversized or heavy loads often requires special permits, which can vary between jurisdictions. Obtaining the necessary permits and adhering to transportation regulations can be time-consuming and costly, potentially affecting project timelines and budgets (Jiang et al. 2018).

Local infrastructure, such as road conditions, bridge capacities, or tunnel clearances, can pose challenges for transporting large prefabricated components. In some cases, infrastructure improvements may be necessary. And because many manufacturers are located in distant locations, inefficient transportation planning can lead to time delays. Regulations restricting cargo transportation and general traffic conditions, especially in densely populated regions, should be investigated (Chiang, Hon-Wan Chan, and Ka-Leung Lok 2006).

Modular construction projects require precise scheduling and coordination between manufacturing facilities, transportation providers, and on-site construction teams. Delays or disruptions in the transportation process can significantly affect project timelines and overall efficiency. Large prefabricated modules may require temporary storage or staging areas before on-site assembly. Securing adequate storage and staging space can be challenging, particularly in urban areas with limited space or high real estate costs. Weather conditions, such as extreme heat, cold, or precipitation, can impact transportation and handling. Protective measures or contingency plans may be necessary for safe and timely transportation (Li et al. 2017).

By developing efficient transportation strategies, investing in specialised equipment, and coordinating closely with stakeholders, the construction industry can overcome these challenges and fully realise the benefits of modular construction.

1.3.5 Economic barriers

Prefabricated construction requires a notable initial investment to set up off-site facilities (Chiang, Hon-Wan Chan, and Ka-Leung Lok 2006), and significant cost overruns may occur if design, communication, logistics, and assembly are not managed (Zhang et al. 2018). The shift to modular construction often requires significant upfront investment in manufacturing facilities, specialised equipment, and workforce training. These initial costs can be a barrier for smaller companies or those hesitant to commit resources to a new construction method. Additionally, conventional project funding methods, where payments are associated with constructing specific deliverables, are not compatible with prefabrication approaches (Steinhardt, Manley, and Miller 2014). Due to unfamiliarity with modular construction or concerns about long-term durability and resale value, lenders, investors, and insurance companies may perceive such projects as higher risk. This can lead to challenges in securing financing and insurance coverage for modular construction projects.

Local conditions, such as labour cost and availability of suppliers, are determining factors in the economic viability of prefabricated construction. In some cases, traditional construction methods may still be more cost-effective or quicker than modular construction. Companies may be reluctant to adopt modular construction if they perceive that it does not provide a clear economic advantage over conventional methods. The construction industry often relies on a fragmented supply chain with multiple suppliers and contractors. This can create challenges for modular construction, which requires a more coordinated and integrated approach to procurement, manufacturing, and logistics, potentially increasing costs.

The shift to modular construction can potentially lead to job displacement for some workers involved in conventional construction methods. Labour unions may resist modular construction to protect their members, increasing labour costs or legal challenges. For instance, if cheap labour is available or modular suppliers are at long distances, using prefabrication might not be economically justifiable (Kamali and Hewage 2016).

Potential economic barriers can hinder the widespread adoption of modular construction in the construction industry, including initial investment costs, financing challenges, limited economies of scale, market demand, competition with conventional construction methods, fragmented supply chain, and labour costs and union resistance. Modular construction benefits from economies of scale, as larger projects can better distribute fixed costs across multiple units. However, smaller projects may not achieve the same level of cost savings, making it less economically viable for some developers or clients. A lack of awareness or scepticism about the benefits of modular construction can negatively affect market demand. This decreased demand can limit the industry's growth and the ability to recoup initial investments.

To overcome these economic barriers, it is crucial to raise awareness of the benefits and potential of modular construction, invest in workforce training and development, and work with financial institutions, regulators, and other stakeholders to create a supportive environment. For example, financial incentives from governments can accelerate the adoption and development of prefabricated construction (Q. Chen, Liu, and Chen 2017; Steinhardt, Manley, and Miller 2014).

1.4 Case study and discussion of prefabrication delivery

1.4.1 Case study specification

The case study is a 9-storey office building located in Brisbane, Australia, which showcases timber from roof to floor (Figure 1). It is Australia's largest and tallest engineered timber office building. Based on off-site construction classification, the investigated case study is categorised as non-volumetric preassembly (type 2 of off-site construction classification).

Figure 1: 3D model of case study building

A concrete structure is used for the basement to the ground and up to level 1. A timber structure comprised of cross laminated timber (CLT) is used for the core from level 1 to level 10. The walls and floors are made of CLT. Glue laminated Timber (Glulam) is used for columns, beams, and bracing. Additionally, there is a structural steel plant room at level 10.

1.4.2 Schedule

This section discusses the duration of the construction project:

- The actual duration of the project (in months) was 6.7% longer than planned.
- Actual start on site to completion of the level 1 concrete structure (in weeks) was 14.8% longer than planned.
- Actual construction of the CLT structure to top out (in weeks) was 10% longer than planned.
- Actual top out to practical completion (in weeks) was 20% shorter than planned.
- Actual installation cycle (in days) was 16.3% longer than planned.

Figure 2: Construction process of level 2

1.4.3 Key learnings

Successfully implementing prefabricated construction requires comprehensive and detailed planning before initiating the project. The case study provides several key lessons about schedule benefits, flexibility, modularisation and dependencies, and challenges in implementing prefabricated construction projects:

- Comprehensive and detailed planning, visual planning and daily updates help ensure a streamlined assembly process and minimise delays. Despite uncertainties and setbacks, the project was completed with only a 15-day delay.
- The project management team demonstrated flexibility by adjusting working hours, increasing the workforce and resources, and coordinating daily with the installation team to recover lost time and maintain productivity.
- The use of prefabricated core modules enabled time savings, increased safety and improved buildability, leading to a cleaner, quieter and more sustainable construction site.
- Effective coordination among various project stakeholders, including suppliers, subcontractors and on-site crews, is critical for ensuring smooth project execution. Accurate design and efficient transportation and logistics are essential for timely project delivery.
- Design and logistics must be meticulously reviewed and planned to ensure success.

The case study highlights the importance of meticulous planning, flexibility, and coordination in overcoming challenges and achieving schedule benefits of prefabricated construction projects. By addressing these factors, construction projects can leverage the advantages of modularisation and deliver successful, high-quality, and sustainable buildings.

1.5 Conclusions and future research opportunities

This chapter highlights the perceived benefits of modular construction, including accelerated construction time, improved installation cycles, and favourable comparisons with conventional methods. The project's top-out to Practical Completion (PC) phase was completed 4 weeks earlier than planned, and hook analysis suggested the potential for a 7-day installation cycle.

Despite challenges such as delivery timings, longer-than-expected installation cycles and additional mobile craneage and overtime work, the modular construction project demonstrated scheduling benefits compared with conventional construction. The case study identifies key lessons in terms of schedule benefits, flexibility, modularisation, dependencies, and challenges in implementing prefabricated construction projects:

- Comprehensive planning, visual planning, and daily updates are crucial for streamlining assembly processes and minimising delays.
- Project management teams must demonstrate flexibility by adjusting working hours, increasing workforce and resources, and coordinating daily with installation teams.
- Prefabricated core modules save time, increase safety, and improve buildability, leading to cleaner, quieter, and more sustainable construction sites.
- Effective coordination among various project stakeholders is essential for smooth project execution, with accurate design and efficient transportation and logistics required for timely delivery.

Addressing technical and process barriers is crucial for the widespread adoption of modular construction in the construction industry. By overcoming these challenges, the industry can capitalise on the benefits of modular construction, such as increased efficiency, reduced waste, and improved quality. The reported benchmarks could not be fully utilised, partly due to the hybrid traditional and modular adoption, which created challenging interfaces. Additionally, the crane became a key resource bottleneck, which was addressed via a mobile crane.

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CHAPTER 2 CONTENTS

CHAPTER 2: PRODUCTISED CONSTRUCTION RISK

Dr Siddhesh Godbole, Prof. Felix Hui, Prof. Lihai Zhang

EXECUTIVE SUMMARY

The present work explored the aspects of risk involved in productised construction management through literature review, market review, stakeholder interactions, and case study analysis. The report is presented in 2 parts: the first part summarised the findings of the literature review on hybrid project risk management, and the latter part introduced a system dynamics-based risks assessment framework to analyse schedule delay risk in productised construction projects.

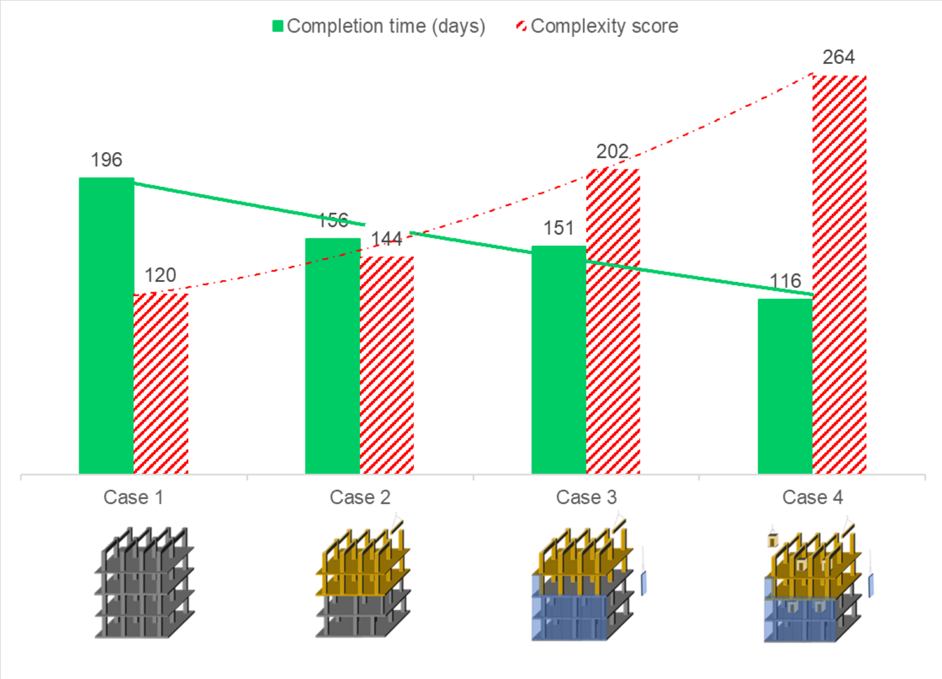
Hybrid project schedules are those with different levels of productisation. Productisation in construction is progressing rapidly with an increasing number of publications targeted to solve problems in the project value chain. These issues were broadly categorised into stakeholder management and change management, supply chain management, project scheduling and optimisation, product typologies in off-site manufacturing, and manufacturing. Each subsection presents a list of sources of uncertainties and associated risks. We consolidated multiple published research papers to curate the lists of uncertainties and risks.

The quantification of risks study summarised a simulation analysis that identified the sources of time risks in productised construction with increasing levels of productisation. The study was based on the Fenner Hall Kambri project, an ANU report provided by Lendlease. The simulation consisted of 4 hypothetical buildings with increasing levels of prefabrication. Completion times and project reliability were estimated for each case.

The study aimed to uncover the sources of uncertainties about how those parameters influenced overall project duration. The graph shows time savings comes at the expense of an increased project complexity score. ‘Project complexity’ reflects ‘the level of attention required in this context’. If the risk assumptions noted above are acceptable, then increasing levels of productisation can have significantly higher complexity (more than twice).

The benefits of off-site construction can be realised only if the stakeholders and project partners are aware of the complexities involved and put control measures place. The following list summarises steps to better understand the complexities:

1. Develop a DfMA-led design of buildings
2. Involve project parties such as the client, the head contractor, designers and manufacturers early.
3. Clearly communicate consistent and compatible data formats and standards.
4. Keep a lessons learnt register to build an experienced team of workers.
5. Augment top-down planning of the critical path method with a bottom-up last planner system, dynamic scheduling and process optimization.
6. Develop a system dynamic approach to the risks involved in the project based on product typology and understanding of the causal connection between different events during construction.



2.1 Introduction

This risk analysis aims to develop a quantification framework for productised construction risk management. We considered 4 case studies with varying levels of productisation and quantified risks using the critical path, PERT and system dynamics approach. Part 1 of the report presents a brief literature survey on risk quantification in productised construction. It also introduces the components of risk assessment framework and how they were deployed. Part 2 presents the time-risk assessment and discusses how productisation influences the risk portfolio.

The 'risk quantification and critical path method literature review' work package was undertaken by the team from the University of Melbourne. The present work summarises:

- a literature survey of project management, scheduling, optimisation, typologies, and risk analysis in off-site construction
- case study analysis of Lendlease projects
- market research for available tools and techniques for off-site risk management
- extensive stakeholder interactions through fortnightly project meetings and workshops.

2.2 Literature review: Productised construction risk

This section presents the findings from the literature review on various aspects of productised hybrid construction management, such as stakeholder management, supply chain management, risk in assessment, schedule optimisation, system dynamics approach, product typologies in industrialised construction etc.

2.2.1 Challenges in hybrid construction projects

A hybrid construction project is one where the construction asset is built by conventional in-situ methods as well as by off-site manufacturing (OSM) methods. As shown in Figure 1, conventional construction is involves a large number of trades on site assembling a complex product made out of multiple simpler parts. By contrast, a productised approach involves delivering complex pre-assembled products to the site for their final installation and assembly. The OSM technologies are also referred to as modern methods of construction, industrialised construction, prefab or prefabricated construction and so on. Recently, market sectors such as schools, hospitals, hotels, student accommodations, low- to mid-rise apartments, police stations, prisons, tourist places etc have seen rising uptake of OSM construction methods. Construction's hybrid nature intersects with many industries, requiring changes to the conventional project management tools.

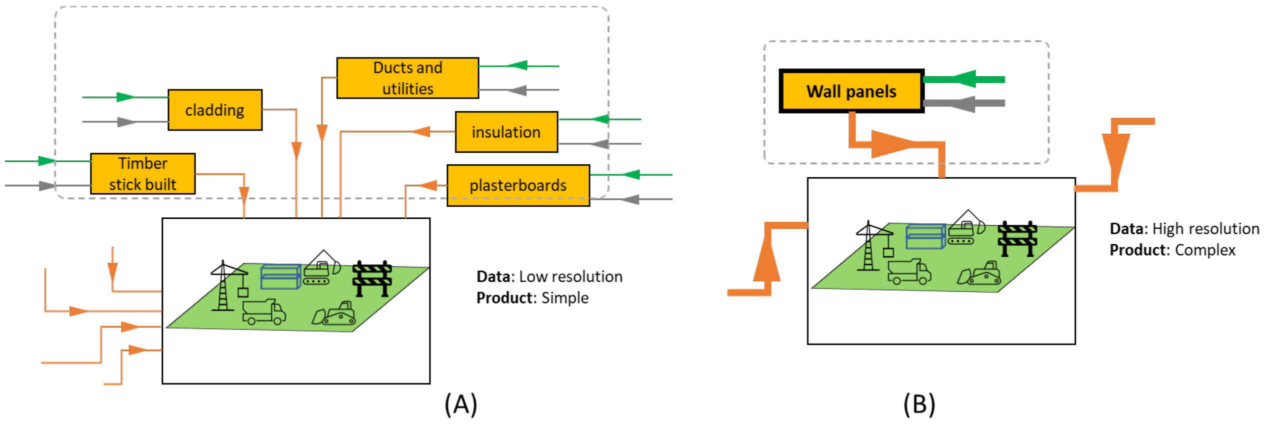


Figure 1 (A) in-situ construction of the wall through individual trades, (B) Productised construction of the wall panel through consolidation of trades to a factory

A survey1 of 100 participants was conducted in Singapore in 2020 to understand lower adoption of prefabricated prefinished volumetric construction. The survey identified the following barriers: change management, ineffective on-site storage, high upfront payment, and transportation issues. The research highlights historical change management theories that may prove useful for current organisations. The literature points to challenges in assembly, real-time information sharing, supply chain management, production scheduling, and reluctance to change when it comes to OSM and productisation (Figure 2).

	Ergonomics Risk assessment	Production scheduling, planning, and optimization	Quality assurance	Real-time information sharing and collection	Energy analysis	Design optimization, automation, and integration	Assembling technique	Site layout design	Supply chain management
Benefits									
Improve quality	0%	0%	50%	20%	0%	19%	27%	0%	0%
Improve safety	100%	0%	0%	20%	0%	3%	0%	33%	0%
Reduce construction cost	0%	22%	0%	20%	50%	10%	0%	33%	36%
Reduce construction time	0%	43%	0%	0%	0%	0%	45%	42%	45%
Reduce labor	33%	9%	0%	0%	0%	10%	0%	0%	0%
Environmentally friendly	0%	0%	0%	0%	100%	0%	0%	0%	0%
Challenges									
Practical and scalability	33%	35%	50%	60%	100%	29%	64%	17%	73%
Reluntant to change	67%	0%	0%	60%	0%	0%	0%	8%	0%
Lack in accuracy	33%	4%	25%	0%	0%	0%	0%	8%	0%
Technical issues	33%	22%	0%	40%	0%	16%	0%	0%	0%
Lack of information interoperability	33%	4%	0%	0%	0%	3%	0%	0%	0%

Figure 2 Heatmap of benefits and barriers as reported in the literature (source: Bing, et al. 2021[2])

[1] Shang, G., Pheng, L.S. and Gina, O.L.T., 2020. Understanding the low adoption of prefabrication prefinished volumetric construction (PPVC) among SMEs in Singapore: From a change management perspective. International Journal of Building Pathology and Adaptation.
[2] Qi, B., Razkenari, M., Costin, A., Kibert, C. and Fu, M., 2021. A systematic review of emerging technologies in industrialized construction. Journal of building engineering, 39, p.102265.

2.2.2 Organisational structure

An effective organisational structure is vital to manage prefabricated buildings. The chain of command starts with the client and ends with peripheral actors such as subcontractors. Newer trends in literature around integrated project delivery (IPD) define IPD as 'an approach that integrates people, systems, business structures, and practices through a multi-party agreement to optimise project results, increase value to the owner, reduce waste, and maximise efficiency through all phases of design and construction'.3 Hong et al (2021) proposed a virtual organisational structure (VoS) that had stronger links with shorter paths among stakeholders and stood to benefit from resource integration, information exchanges, and communications (Figure 3). In this VoS, the stakeholders at the core layer could achieve information-free flow through early involvement and communication improvement. The VoS in Figure 3 also provides a suggestive framework for early contractor involvement (ECI)4.

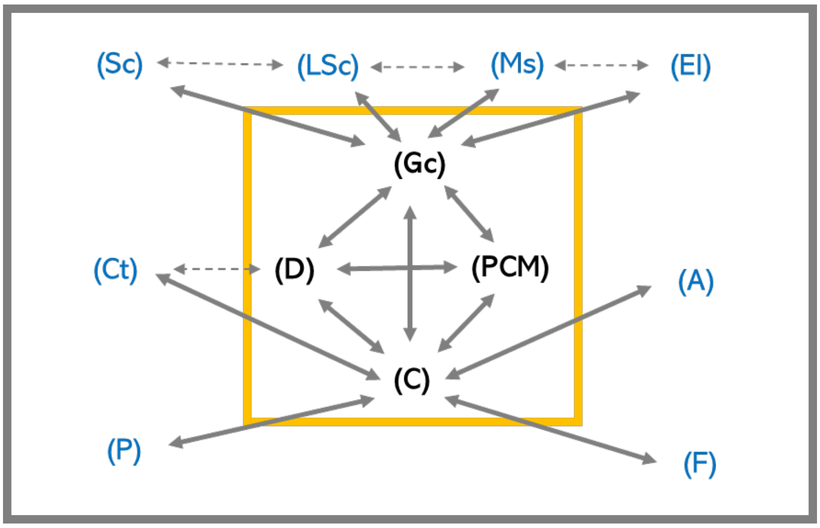


Figure 3 Virtual organisational structure where: Client (C), designer (D), general contractor (Gc), precast manufacturer (PCM), subcontractor (Sc), labor subcontractor (LSc), material supplier (Ms), equipment leaser/supplier (El), supervisor (S), consultant (Ct), auditor (A), prospector (P), financial institution (F), local government (Lg)

The extent of adoption of OSM is governed by parameters such as market readiness, social perception, regulatory environment, policy, legislation and compliance standards, procurement strategies, and organisational structures. Studies show different levels of these parameters create different pressures on resource utilisations and may play a key role in the adoption of OSM methodologies[5].

- Coercive pressure usually arises from demands placed on players who have a resource-dependent relationship with one another and are required to act in a specific way.
- Normative pressure arises when standards and code compliance requirements are the drivers.
- Mimetic pressure arises from uncertainty and is characterised by firms' imitation of the actors they trust or aspire to be.

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[3] Mesa, H.A., Molenaar, K.R. and Alarcón, L.F., 2019. Comparative analysis between integrated project delivery and lean project delivery. International journal of project management, 37(3), pp.395-409.
[4] Xue, H., Sun, T., Ling, F.Y. and Wang, L., 2021. Redesigning the virtual organisational structure for the management of prefabricated buildings. International Journal of Construction Management, pp.1-17.
[5] Oti-Sarpong, K., Shojaei, R.S., Dakhli, Z., Burgess, G. and Zaki, M., 2022. How countries achieve greater use of offsite manufacturing to build new housing: Identifying typologies through institutional theory. Sustainable Cities and Society, 76, p.103403.

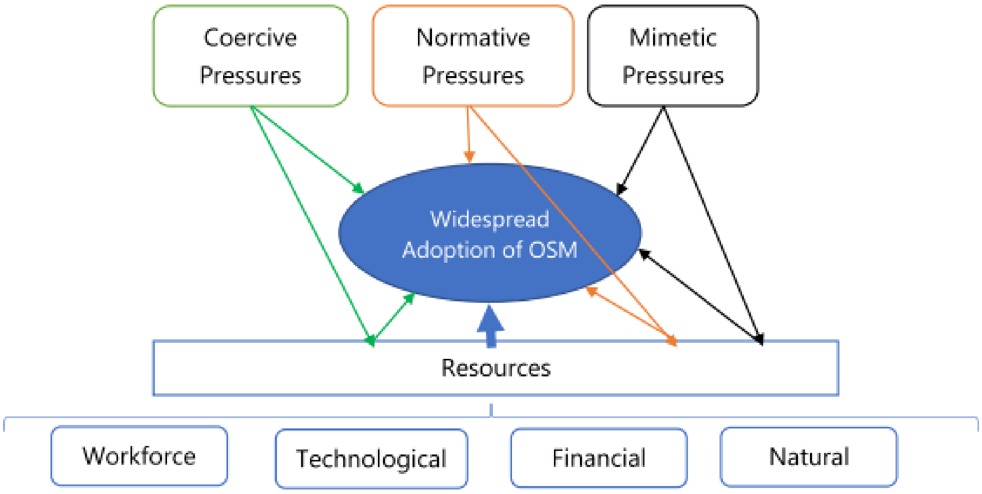

Figure 4 Three pressures in market dictating resource utilisation towards adoption of OSM (source: Oti-Sarpong, K. 2022)

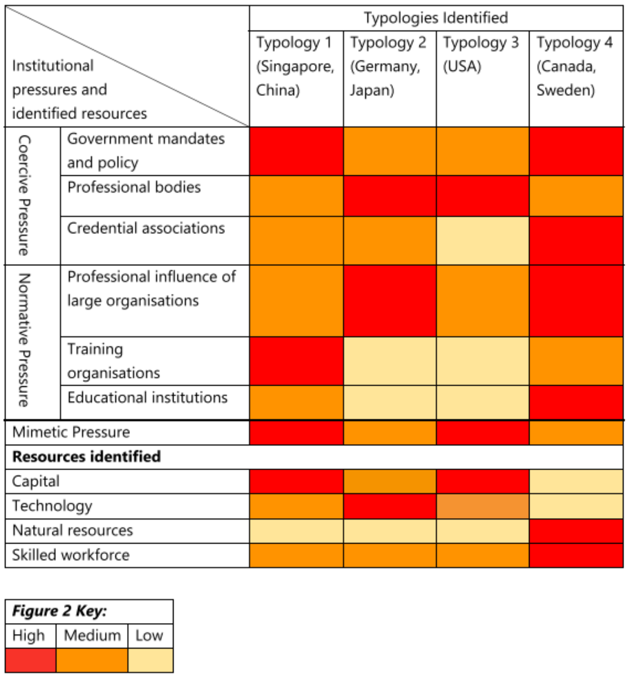

Figure 5 Typologies of achieving greater use of OSM across countries (source: Oti-Sarpong, K. 2022)

2.2.3 Supply chain management

The heightened risk exposure of construction supply chains requires greater resilience. A systematic literature review conducted by Ekanayake, E.M. et al (2020)[6] consolidated appropriate supply chain capabilities that construction firms must nurture and develop further:

- Flexibility: the ability to mobilise resources quickly when required
- Capacity: availability of resources to enable continuous production
- Efficiency: Capability to produce outputs optimally

[6] Enshassi, M.S., Walbridge, S., West, J.S. and Haas, C.T., 2020. Probabilistic risk management framework for tolerance-related Issues in modularized projects: Local and global perspectives. ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, Part A: Civil Engineering, 6(1), p.04019022.

- Visibility: information on current operating status quo
- Adaptability: ability to modify processes in response to disruptions
- Anticipation: Ability to detect potential future disruptive events
- Recovery: Ability to return to normal operational state quickly
- Dispersion: Decentralisation of resources and clients
- Collaboration: Ability to work effectively with other parties for mutual benefit
- Market position: status of an organisation or its services in specific markets
- Security: Defence against deliberate intrusions
- Financial strength: Capacity to absorb fluctuations in cash flow

In supply chain management literature, the following areas were found to receive higher attention:[7]

- precast production
- storage and inventory
- delivery and transportation
- performance of the supply chain.

A systematic literature review conducted by Bao et al (2021) stressed the importance of collaboration, building information modelling (BIM), and supply chain management through social network analysis (see Figure 6).

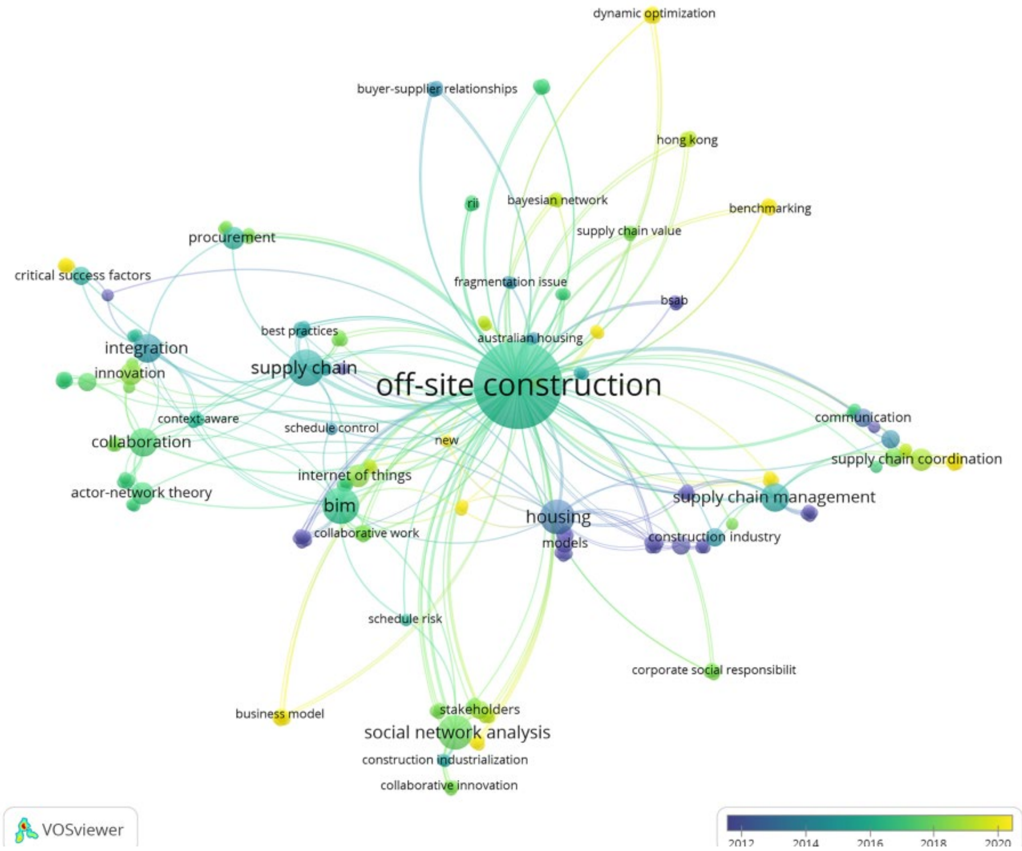

Figure 6 Co-occurrence of keywords in off-site supply chain management literature (source: Bao et al. 2021[8])

[7] Wang, Z., Hu, H., Gong, J., Ma, X. and Xiong, W., 2019. Precast supply chain management in off-site construction: A critical literature review. Journal of Cleaner Production, 232, pp.1204-1217.

[8] Nguyen, B.N., London, K. and Zhang, P., 2021. Stakeholder relationships in off-site construction: A systematic literature review. Smart and Sustainable Built Environment.

A survey of 48 respondents involving consultants, general contractors, owners, and subcontractors identified the following problems with the construction supply chain: (i) shortage of skilled labour, (ii) late design changes, (iii) poor site attributes and logistics, (iv) contractual risks and disputes, (v) lack of adequate collaboration, and (vi) challenges related to tolerances and interfaces as main pain points in construction projects.[9]

Complex designs of OSM products (type 4 products in Figure 8) require upstream and downstream collaboration in the supply chain. Product designers must be aware of the manufacturing and assembly capabilities downstream and resulting geometric tolerance issues. A proposed framework for geometric tolerance management incorporates constraint identification, planning for tolerances, communication and data sharing, and control measures.[10]

Sources of uncertainties

Uncertainties associated with productised construction can be systematically explored and categorised as shown in Table 1. The case study analysis, literature survey, and interviews performed by Yang Y. et al (2021) were condensed into Sources of Uncertainties (SoUs) for different categories in OSM and quantified in terms of their perceived likelihood and impact on overall project value.[11]

Table 1 Framework of SoUs in off-site logistics of high-rise modular buildings.

Area	Sources of Uncertainties	Perceived likelihood	Impact on value
Off-site logistics processes	1. Lack of skilled workers in the factory	AAA	AAAB
	2. Machine breakdowns or unavailable	AA	AAA
	3. Poorly designed manufacturing workflows	AAA	AAAB
	4. Poorly designed factory	AAB	AAA
	5. Long distance	AAAB	AAA
	6. Improper protection during	AAA	AAA
	7. Additional escort arrangement for large-size module	AAA	AAB
	8. Too small overall storage capacity	AAA	AAAB
Demand side	9. Late design changes after production starts	AAAB	AAAB
	10. Unsupportive design decisions	AAA	AAA
	11. Highly diversified modular design	AAA	AAAB
		AAAB	AAA

[9] Abdul Nabi, M. and El-adaway, I.H., 2021. Understanding the key risks affecting cost and schedule performance of modular construction projects. Journal of Management in Engineering, 37(4), p.04021023.
[10] Talebi, S., Koskela, L., Tzortzopoulos, P. and Kagioglou, M., 2020. Tolerance management in construction: A conceptual framework. Sustainability, 12(3), p.1039.
[11] Yang, Y., Pan, M., Pan, W. and Zhang, Z., 2021. Sources of uncertainties in offsite logistics of modular construction for high-rise building projects. Journal of Management in Engineering, 37(3), p.04021011.

	12. Client and supplier have different levels of quality acceptance for the finished module	AAB	AAAB
	13. Variable installation schedules	AA	AAA
	14. Module damage during installation		
Supply side	15. The poor performance of material suppliers	AAB	AAA
	16. Long or uncertain lead time of material supply	AAA	AAAB
	17. Too complicated material procurement	AAA	AAAA
	18. Inaccurate material specification	AAB	AAA
Planning and control systems	19. Ineffective planning and scheduling	AAA	AAAA
	20. Over prescriptiveness of client to supplier	AAB	AAA
	21. Immature technical problems	AAB	AAA
	22. Unfitness of technology with real practices	AAB	AAA
	23. Poor information sharing and synchronisation	AAAB	AAA
	24. inefficient information management	AAA	AAA
	25. inadequate quality assurance	AAA	AAAB
	26. lack of skilled inspection team for off-site logistics	AAA	AAAB
Environment	27. Long and unpredictable time for customs checks	AAAB	AAB
	28. Traffic congestion	AAAB	AAB
	29. Severe and extreme weather	AAA	AAB
	30. Fluctuating fuel prices	AAB	AA

AA=2.00–2.49, AAB=2.50–2.99, AAA=3.00–3.49, AAAB= 3.50–3.99, AAAA= 4.00–4.50, AAAAB = above 4.51.

Productised supply chains

Tong et al (2021)[12] surveyed the Australian low-rise market for prefabricated construction and concluded:

- component-based prefabrication is most suitable for the Australian low-rise building market
- the best option for procuring prefabricated products is through Australian manufacturers followed by Australian suppliers/dealers and then overseas dealers
- panelised prefabrication and component-based prefabrication are most suitable for Australian manufacturers
- modular prefabrication is most suitable for overseas manufacturers while component-based prefabrication is most suitable for Australian suppliers/dealers.

[12] Lin, T., Lyu, S., Yang, R.J. and Tivendale, L., 2021. Offsite construction in the Australian low-rise residential buildings application levels and procurement options. Engineering, Construction and Architectural Management.

2.2.4 Manufacturing

Production management introduces additional challenges that are rarely present in conventional construction project management. Productised construction projects involve building products that are pre-assembled and manufactured in a factory. The manufacturing activity may be decoupled from the actual construction schedule, so must be carefully managed in the planning phase. The correct set of inputs that deliver compliant components (products) to the site is an error-free design inspired by the Design for Manufacturing and Assembly (DfMA) philosophy, adequate lead times, conducive risk allocation, supply chain management, production management, and accurate scheduling. Buffer management can be leveraged to alleviate problems in tight synchronisation between OSM and on-site construction.[13] Several methods such as project-led flow and just-in-time (JIT) have been explored for production planning coupled with the last planner system (LPS). The authors emphasise 3 important principles in implementing LPS in construction:

- 'All plans are forecasts; all forecasts are wrong.'
- 'The longer the forecast, the more wrong it becomes.'
- 'The more detailed the forecast, the wronger it is.'

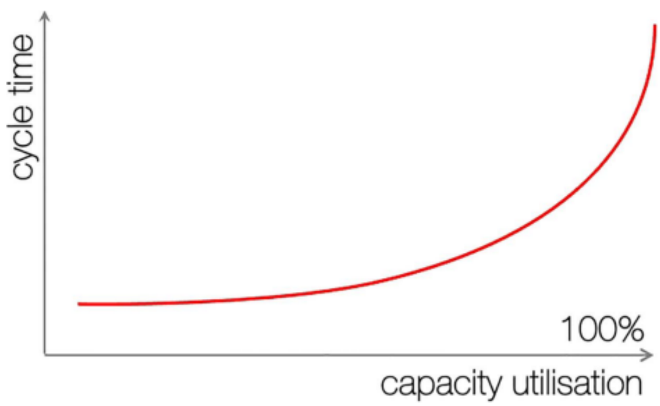

Figure 7 Capacity utilisation curve adopted from (Hopp and Spearman, 2000[14])

Figure 7 (from the Factory Physics guide to managers) emphasises the relationship between cycle time and capacity utilisation of plant machinery. From the OSM and construction perspective, it is vital to understand the upper bounds on the cycle time of the product being produced in a factory and the level of utilisation of the machinery of optimised production management. The curve shows cycle time for a product increases non-linearly as the production facility is pushed to its limits. Failing to fully implement JIT across the construction supply chain can exacerbate productivity and efficiency gains. The level of coordination required to operate the entire construction supply chain may not be feasible through the conventional critical path method approach to scheduling, rendering the use of OSM methods disappointing. LPS has been shown to alleviate the problem.

2.2.5 Product typologies

Productisation in construction primarily stems from repeatability in parts and standardisation of design. The more the standardisation and repeatability, the easier productisation is. Categorising off-site manufactured products can help planners, legislators, designers, and insurers work around

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[13] Mossman, A. and Sarhan, S., 2021. Synchronising off-site fabrication with on-site production in construction. Construction Economics and Building, 21(3), pp.122-141.

[14] Hopp, W.J. and Spearman, M.L., 2011. Factory physics. Waveland Press.

the products. The common use terms are important and enable development of various standards for compliance and ease of adopting OSM, as pointed out in AMGC (2021).[15]

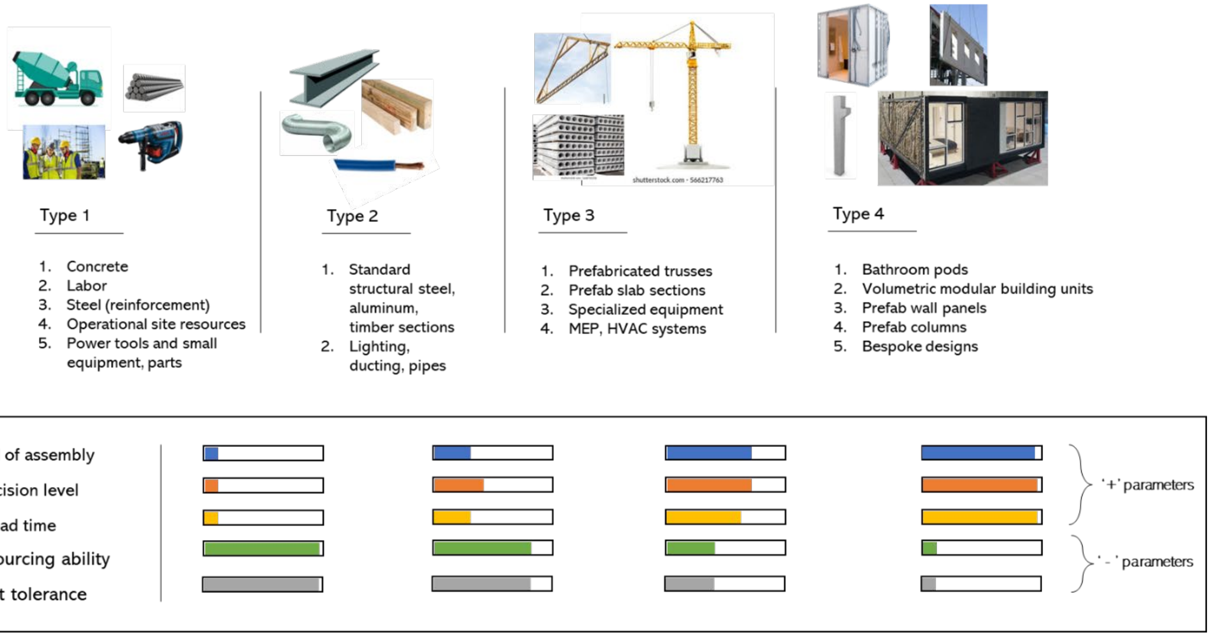

Figure 8 Product typologies according to assembly levels

From Figure 8, the level of assembly can be used to classify OSM products in a hybrid construction project:

Type 1 items represent the resources and materials that require the highest amount of work on-site (i.e., products with the least amount of pre-assembly before arriving at the site). Being closest to their raw state, such items can be re-sourced easily and generally have high fault tolerance. Examples include human labour, power tools, ready mix concrete, reinforcing bars, and timber.

Type 2 items represent value-added resources and materials that require planned processes on site to use them. Such items sit further from their raw states than type 1 items because value-added activities increase the level of pre-assembly (or pre-work) involved before arriving at the site. They can be tailored to suit a specific building, so involve a higher-level decision making than type 1 items. Their ability to be re-sourced from a different supplier is usually lower than type-1 items because of higher pre-assembly. Examples include pre-cut structural steel beams and columns, MEP (mechanical, electrical and plumbing) services and HVAC (heating, ventilation, air conditioning), and timber.

Type 3 items are pre-fabricated elements and equipment that are bespoke to a construction site and building type. These items undergo a considerable amount of pre-assembly or pre-work via value-added activities. Products under this category combine different materials, parts, and project-specific geometric and functional information to produce a customised element and hence require a higher level of decision making. Their re-sourcing ability is diminished further than type-2 items. The fault tolerance to geometric and functional variability is lower. Examples include prefabricated trusses, cranes, prefab slab sections, timber wall framing, and steel wall framing.

Type 4 items are prefabricated products that are made to order for a specific building project. These items have the highest amount of pre-assembly and require the least amount of on-site work, mostly involving lifting, placement and installation. The decision about such items generally requires the highest level of coordination between multiple project stakeholders such as the client,

[15] Regulatory barriers associated with prefabricated and modular construction. HIA. AMGC, Nov 2021.

the head contractor, the manufacturer, and the project manager. They have the lowest fault tolerance and re-sourcing ability because they are unique to each manufacturer and the project and very unlikely to be found elsewhere. Examples include volumetric modular units, bathroom pods, prefab columns and beams, prefab wall sections, prefab floor, and ceiling cassettes.

Many studies have tried to classify OSM products. For example, Ginigaddara et al (2019)[16] offered a broad list of categories such as components, panels, pods, modules, complete building, and flat pack solutions. Another study classified industrialised building systems by different themes.[17] From a preparation perspective, OSM products could be classified into materials, building components, assembly, and chunks (Figure 9).

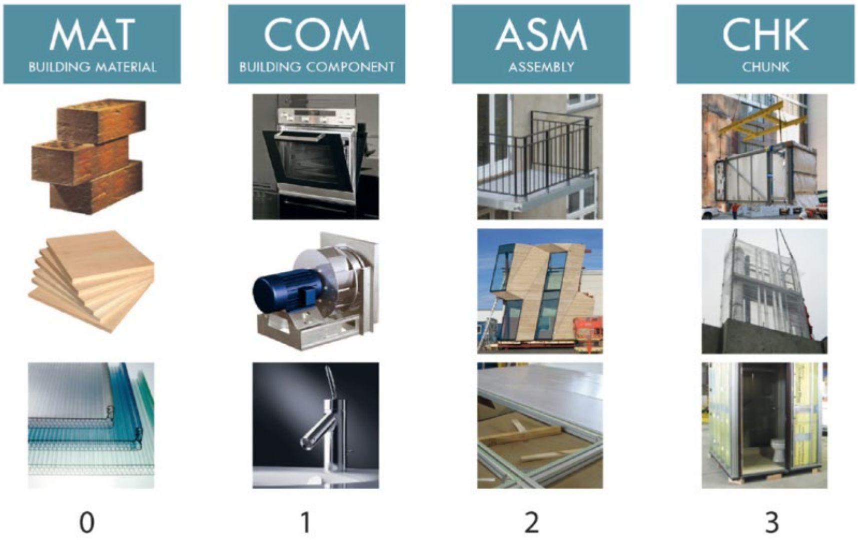

Figure 9 Typology from a preparation perspective

From a standardisation perspective, we propose 4 categories: bespoke, made-to-order, cut-to-fit, and off-the-shelf (Figure 10).

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[16] Ginigaddara, B., Perera, S., Feng, Y. and Rahnamayiezekavat, P., 2019. Typologies of offsite construction.
[17] VIBÆK, K.S., 2012. System structures in architecture: Towards a theory of industrialised architecture. In Proceedings of the Association of Collegiate Schools of Architecture, Fall Conference (pp. 232-239).

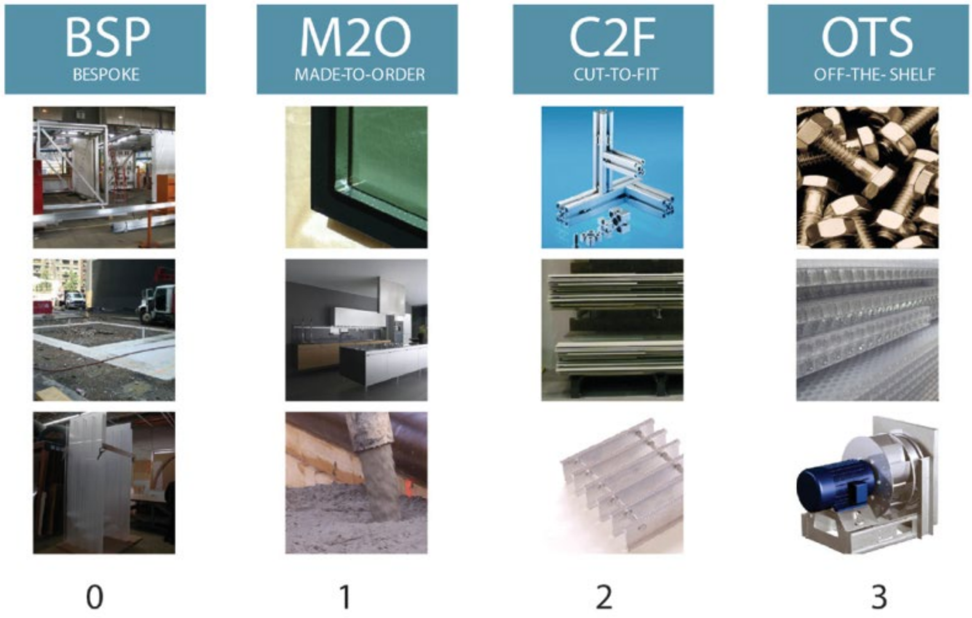

Figure 10 Typology from a standardisation perspective

2.2.6 Project management and scheduling

Common terminologies

PERT/CPM (Program evaluation and review technique/ Critical path method)

- Predict activity duration and total project duration by incorporating activity risk. Resources are assumed to be unconstrained.
- PERT assigns activity duration based on probabilistic methods (beta curve/ 3-point method) in a simplistic form. Optimistic time (b), pessimistic time (a) and a meantime (m) of completion of activity are the inputs for each activity. Based on that an expected time for an activity is calculated as $t = \frac{a+4m+b}{6}$.

RCPSP (Resource constraint project scheduling problem)

- This evaluation technique accounts for resource availability and schedules the activities accordingly.
- Resources could be daily cash flow, labour hours, site space available, cranes, transport trucks, and so on.

SRA (Schedule risk analysis)

- This methodology evaluates multiple critical paths based on elaborate Monte-Carlo simulations.
- Many activities that aren't on a critical path as per deterministic methods can become critical due to their inherent uncertainties.

Heuristic approaches

- These approximate methods are normally deployed to construction schedules based on priorities.
- Priorities could be activity-based, network-based, resource-based, or personnel based.

LSM (Linear scheduling method)

- This method is used to schedule repetitive tasks. Its advantage over the CPM is that it aims to maximise the resource allocation.

LPS (Last planner system)

- This approach is based on realistic goals that CAN be and WILL be completed as promised by the last planners themselves.
- The idea is to incorporate 'pull planning' rather than conventional 'push planning'. In push planning, the planners push down the set of activities in the planning document that according to them SHOULD be completed on given milestones. By contrast, pull planning takes the planning bottom up, where the schedule is revised based on what can be performed in any given time window as assessed by those who are at the tail-end of the execution schedule.

CCPM (Critical chain project management)

- This approach is synonymous with resource constraint project scheduling problems (RCPSP) in which critical path analysis is carried out with resource availability in mind.

PLTH (Production lead time hedging)

- This approach involves aggressively setting due dates for an off-site manufacturer accounting for the tardiness in a project.

BRH (Buffer resource hedging)

- This approach is conceptually similar to the PLTH, buffer resource hedging (mostly quantity, space, or time) and safeguards against uncertainties. Uncertainties could be changes in due dates, sudden changes in demand, transportation logistic unavailability and so on.
- Standby equipment is an example of hedging against equipment failure on site. Arranging for the extra resource (labour, cash, time, materials, equipment) is a way to hedge the project schedule against uncertainties.
- This is a trade-off between suffering the consequences of unfavourable events and the cost of safeguarding against them.

ECI (Early contractor involvement)

- This approach involves engaging the head contractor before the tendering process.
- It could decrease project duration by streamlining the subcontracting and design process.

PP (Product platforms)

- This approach involves a standardised repository of productised components in off-site construction. Repetitive components in a project could easily be standardised and maintained on a product platform.

CODP (Customer order decoupling point)

- This is a point in the value chain where the product is attached to specific client order. This approach separates the product from the 'general' assembly and makes it specific to a particular project/client.
- Tracking the CODP in a value chain is a useful tool to gauge the standardisation of a process. The closer the CODP to the customer, the higher the standardisation. A bespoke conventional house has CODP extremely early in the value chain, whereas a standard automobile is not decoupled until it is sold to a customer through a dealer.

SNA (Social network analysis)

- This approach analyses relationships/contracts between different stakeholders in a construction project.
- The issues evaluated include financial transactions and performance incentives, contractual relationships, a range of communication types and modes, information and knowledge transfer, risk transfer, abuse of power, and conflict resolution.

Student's syndrome and Parkinson's law

- This approach involves planned procrastination to suit personal interests (students' syndrome). Work expands to fill the time available for its completion (Parkinson's law).

Hybrid construction risk

Delayed project schedules are common in construction. Delays to individual activities on the critical path have the highest impact ule. Activity buffers and risk allocation agreements could safeguard the project manager against time delays and cost overruns respectively. The challenges arising from the complex and interconnected nature of OSM-based hybrid construction schedules are stretching the established methods of project scheduling and management to their limits. Understanding the risks involved in hybrid construction projects thus becomes paramount.

A US survey in 2021 of 48 experienced construction professionals18 highlighted the top 7 risks in OSM:

- shortage of skilled and experienced labour
- late design changes
- poor site attributes and logistics
- the unsustainability of design for modularisation
- contractual risks and disputes
- lack of adequate collaboration and coordination
- challenges related to tolerances and interfaces.

CCPM is integrated with LPS and LSM to solve the problems arising due to inefficiencies in the critical path method to address the challenges of hybrid construction schedules. Salama T. et al (2020) demonstrated that combining CCPM, LPS and LSM could save 10–12% of the construction schedule with 90% confidence.[19]

Scheduling

Scheduling is a fundamental aspect of construction projects and plays a key role in their success. Mainstream research areas in construction project scheduling literature include:[20]

- assessing schedule health, metrics, planning and control
- using line of balance, analytic methods and PERT
- optimising time-cost tradeoff, time-cost-quality trade-off, resource allocation and levelling
- identifying schedule risks
- using BIM, lean project schedule, GIS and big data.

Typical risks in scheduling include the following:

- the inefficiency of design approval
- inefficiency in design data transition
- low information interoperability between different enterprise resource planning systems (ERPs)
- the design information gap between designer and manufacturer
- delay of delivery of precast element to the site
- logistics information inconsistency due to human errors
- misplacement on the storage site due to carelessness
- tower crane breakdown and maintenance
- inefficient verification of precast due to ambiguous labels
- slow quality inspection procedures.

System dynamics

Recent advancements in dynamic project control literature have seen the emergence of the system dynamics (SD) approach. Unlike conventional approaches, SD considers the dynamic relationship between various events in the construction schedule and their causal connections so construction

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[18] Abdul Nabi, M. and El-adaway, I.H., 2021. Understanding the key risks affecting cost and schedule performance of modular construction projects. Journal of Management in Engineering, 37(4), p.04021023.
[19] Salama, T., Salah, A. and Moselhi, O., 2021. Integrating critical chain project management with last planner system for linear scheduling of modular construction. Construction Innovation.
[20] Derbe, G., Li, Y., Wu, D. and Zhao, Q., 2020. Scientometric review of construction project schedule studies: trends, gaps and potential research areas. Journal of Civil Engineering and Management, 26(4), pp.343-363.

managers can reasonably assess the project schedule.21 Construction schedules change as the project progresses which requires a dynamic scheduling22 approach. SD enables dynamic scheduling by emphasising the consequences of control measures. Table 2 presents a typical comparison between the conventional critical path method and the system dynamics approach.[23]

Table 2 Comparison of SD approach with critical path method

Perspective	Critical path method	System dynamics
Behavior	Linear	Linear and nonlinear
Data type	Quantitative	Quantitative and qualitative
Capturing managerial corrective actions	Low	Very high
Realistic for project acceleration	Low	Very high
Level of detail and focus	Activity	Holistic and feedback
Risks and uncertainty management	High	Very high
Evaluating impacts of uncertainty	High	Very high
Evaluating decision level	High	Very high
Estimating accurate project cost, duration, and resources	High	Very high
Work schedule	High	Very high
Project control and monitoring	Yes	Yes
Showing interrelationships	Yes	Yes
Accounting for feedback effects	Yes (Low)	Very high
Work specification	Yes	No
Handling multi-interdependent components	No	Yes
Productivity impact consideration	No	Yes
Handling multiple feedback processes	No	Yes
Handling nonlinear relationships	No	Yes
Computational capability for predictions	No	Yes

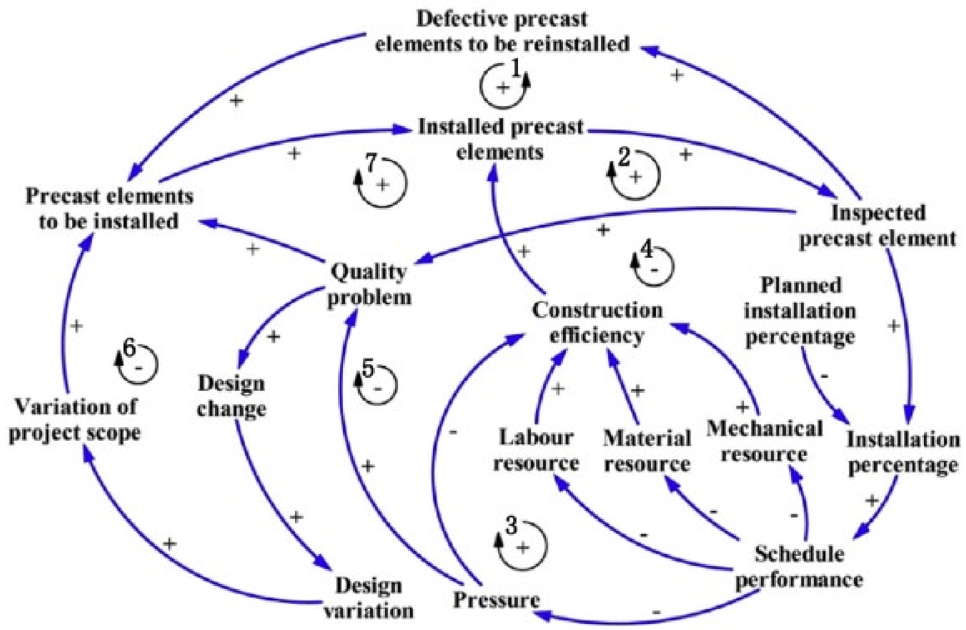

Figure 11 Causal loop of system dynamics (source: Li, C.Z. et all. 2017[24])

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[21]Wu, Z., Yang, K., Lai, X. and Antwi-Afari, M.F., 2020. A scientometric review of system dynamics applications in construction management research. Sustainability, 12(18), p.7474.
[22] Peña-Mora, F. and Li, M., 2001. Dynamic planning and control methodology for design/build fast-track construction projects. Journal of construction engineering and management, 127(1), pp.1-17.
[23] Abotaleb, I.S. and El-adaway, I.H., 2018. Managing construction projects through dynamic modeling: Reviewing the existing body of knowledge and deriving future research directions. Journal of management in engineering, 34(6), p.04018033.
[24] Li, C.Z., Shen, G.Q., Xu, X., Xue, F., Sommer, L. and Luo, L., 2017. Schedule risk modeling in prefabrication housing production. Journal of Cleaner Production, 153, pp.692-706.

Optimisations

Scheduling of hybrid construction projects benefits from algorithmic optimisation of moving gears in the supply chain. Schedule optimisation literature points to various algorithmic techniques that have been deployed. The authors developed scheduling optimisation considering product due date uncertainty, emphasising the importance of JIT.[25] Wei H. et al (2021) deployed a genetic algorithm (GA) in choosing optimal resource management schemes to save time and cost. The GA optimisation reduced construction time by 19% and cost by 9%.[26] Wei et al (2020) adopted the simulated annealing (SA) technique to find an optimised solution for operation planning considering various risks. The study dealt with multiple manufacturing facilities providing multiple components to a construction site.[27] Jiang et al deployed GA-based optimisation techniques to maximise the profit for the manufacturer under multiple orders, limited capacity, and mould sharing constraints. The study discovered a profit-based criterion that would be most effective for precast manufacturers under dynamic order changes.[28] Optimisation of transportation logistics focuses on efficient ways of ordering and scheduling deliveries to the site based on truck capacity, emissions, geometric limitations, and production rate.[29] A comprehensive review of artificial intelligence-based risk assessment methods for capturing complex risk interdependencies in construction projects can be found here.[30]

2.2 Quantitative risk assessment

This section quantifies the time-risk involved in productised construction through a case study simulation. The uncertainties involved in productised building construction are stipulated using a SD approach with causal relationships. The critical path was inspired by the Fenner Hall building at the Kambri ANU Acton campus (Figure 12), provided by the project stakeholder Lendlease. The quantitative risk assessment was performed on 4 hypothetical buildings containing different levels of productisation. We used PERT to produce the risk score and the project duration with confidence bounds on its completion time.

2.2.1 Case study: Fenner Hall, ANU

The Fenner Hall schedule analysis involves a conventionally built reinforced concrete structure as a control structure and the same structure built with prefabricated CLT. The CLT structure contains an in-situ concrete podium up to level 2 and a CLT structure from level 3 to level 9.

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[25] Yazdani, M., Kabirifar, K., Fathollahi-Fard, A.M. and Mojtahedi, M., 2021. Production scheduling of off-site prefabricated construction components considering sequence dependent due dates. Environmental Science and Pollution Research, pp.1-17.

[26] He, W., Li, W. and Meng, X., 2021. Scheduling Optimization of Prefabricated Buildings under Resource Constraints. KSCE Journal of Civil Engineering, 25(12), pp.4507-4519.

[27] Chen, W., Zhao, Y., Yu, Y., Chen, K. and Arashpour, M., 2020. Collaborative scheduling of on-site and off-site operations in prefabrication. Sustainability, 12(21), p.9266.

[28] Jiang, W., Wu, L. and Cao, Y., 2020. Multiple precast component orders acceptance and scheduling. Mathematical Problems in Engineering, 2020.

[29] Almashaqbeh, M. and El-Rayes, K., 2021. Minimizing transportation cost of prefabricated modules in modular construction projects. Engineering, Construction and Architectural Management.

[30] Afzal, F., Yunfei, S., Nazir, M. and Bhatti, S.M., 2019. A review of artificial intelligence based risk assessment methods for capturing complexity-risk interdependencies: cost overrun in construction projects. International Journal of Managing Projects in Business, 14(2), pp.300-328.

Figure 12 Fennel Hall, ANU

The construction schedule of conventionally built Fenner Hall with in-situ concrete is depicted in Figure 13, and the schedule containing CLT superstructure over a 2-storeyed in-situ concrete podium is depicted in Figure 14. Conventional construction of Fenner Hall contains the following components in its master schedule:

- construction of the concrete structure
- formwork removal
- façade erection and installation
- internal fit-outs and preparation for handover.

The critical path of the high-level master schedule anchors around the following events:

- removal of formwork after concrete structure attains the nominal strength up to level 2
- façade installation, shop front, and plumbing work up to level 2 after stripping of the formwork
- internal fit-outs involving wet works, plastering, MEP, HVAC.

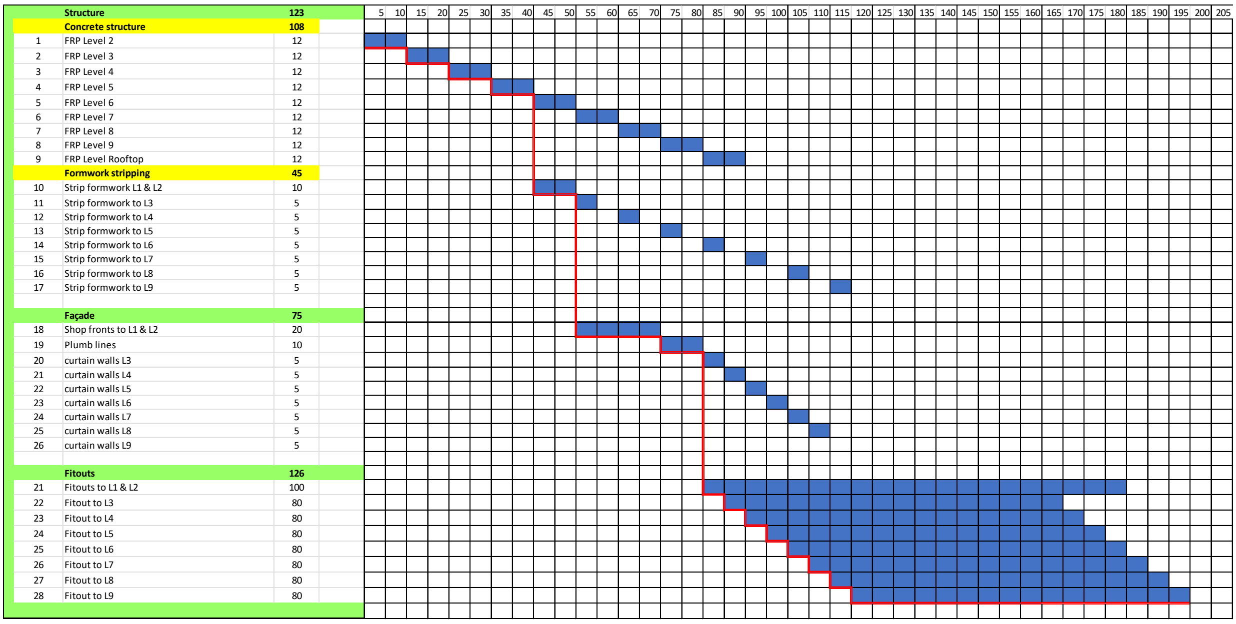


Figure 13 Schedule for conventionally built Fenner Hall structure

By contrast, the CLT structural schedule for the same structure involves the following components in its master schedule (Figure 14):

- construction of concrete podium structure
- formwork removal
- erection of CLT panels from level 3 to level 9
- curtain wall erection and installation
- internal fit-outs and preparation for handover.

The critical path of the project involving CLT superstructure anchors around the following events:

- Erection of CLT panels beyond level 3, after completion of concrete podium
- Removal of formwork after the concrete structure attains its nominal strength
- Shop front work and plumbing up to level 2
- Internal fit-outs involving wet works, MEP, HVAC and plastering

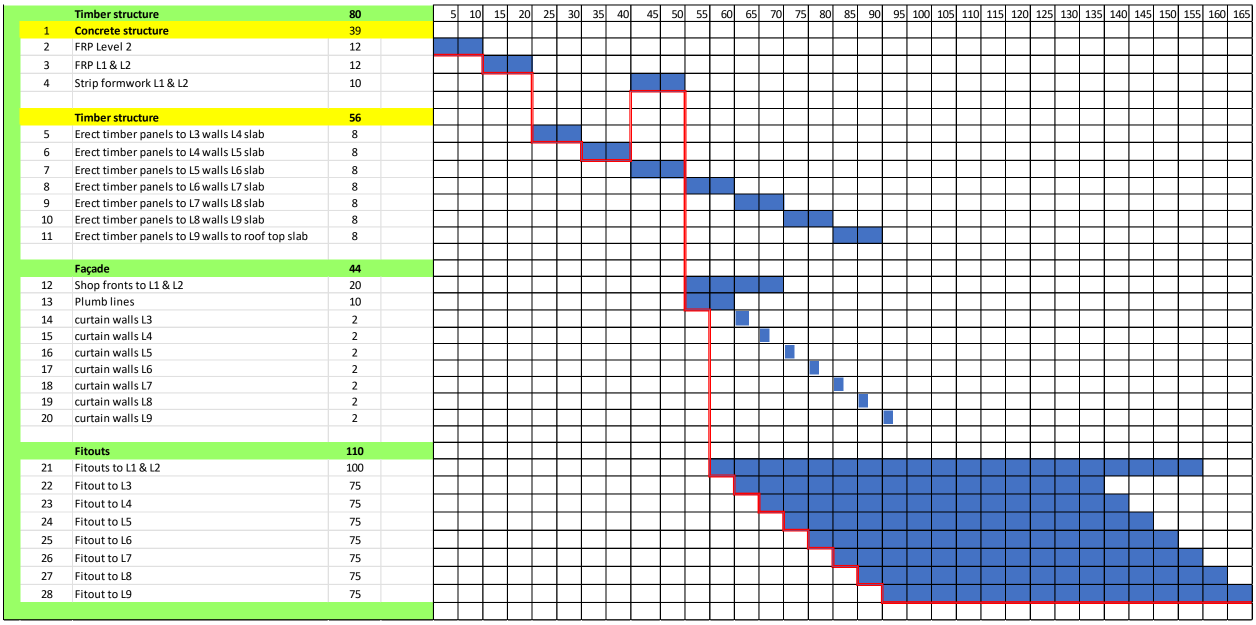


Figure 14 Schedule for CLT structure for Fenner Hall

2.2.2 Case study analysis (Simulation)

Based on the project schedule for Fenner Hall and as shown in Figure 13 and Figure 14, we conceived 4 hypothetical building schedules for a similar building structure. The design and functional outline of the structure was the same, but each schedule involved a different level of productisation (Figure 15).

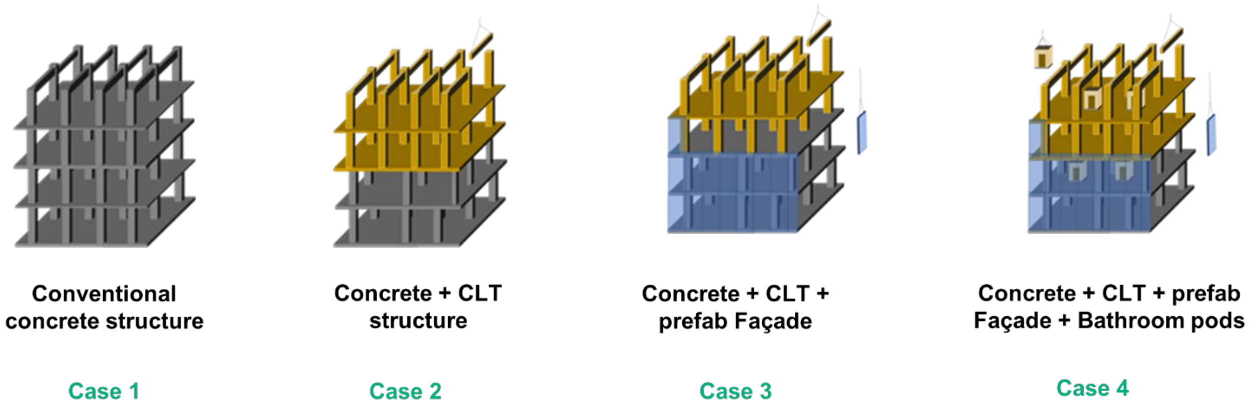


Figure 15 Four hypothetical buildings with increasing levels of productisation

- Case 1 depicts a scenario where the superstructure of the building is entirely constructed with in-situ concrete.
- Case 2 contains a concrete podium with a prefabricated CLT superstructure (similar to the control structure of Fenner Hall, ANU).
- Case 3 has a higher level of productisation and involves prefabricated façade systems along with prefabricated CLT panels on concrete podium structure (similar to the Fenner Hall, ANU).
- Case-4 has the highest levels of productisation, including prefabricated bathroom pods, prefabricated facades. and prefabricated CLT on a concrete podium.

2.2.3 Critical path method

The schedules for respective cases are provided in Figures 16 to 19. The critical path of each schedule was developed analogous to the Fenner Hall construction schedule as described in Figure 14. In the following figures, the construction schedule of activities is marked in grey under the 'construction phase'. Black demarcates the 'planning phase' involved with each construction phase activity and is marked indicatively. The design and ideation phases indicated the time involvement of each activity for different levels of productisation.

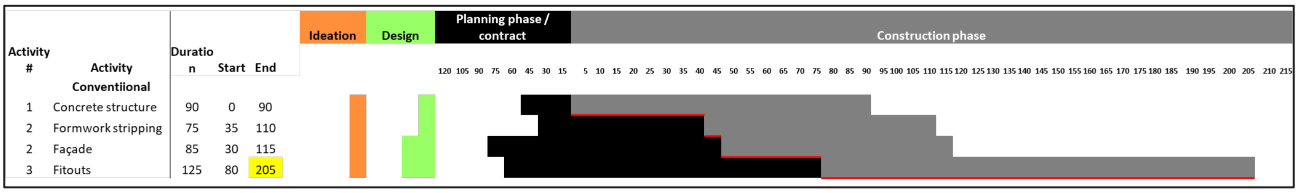


Figure 16 Project schedule for case 1

The schedule for case 1 is similar to that of the conventional Fenner Hall project schedule. The critical path for such a structure follows the removal of formwork upon concrete curing, installation of curtain walls, plumbing, and fit-outs.

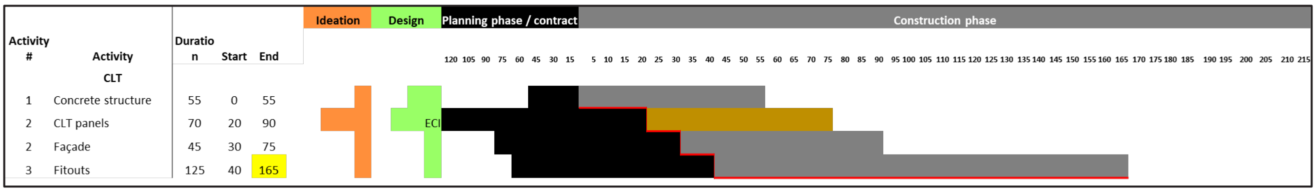


Figure 17 Project schedule for case 2

The schedule for case 2 is adapted from the CLT structure in the Fenner Hall construction schedule.[31] The critical path follows similar milestones as described in Figure 14.

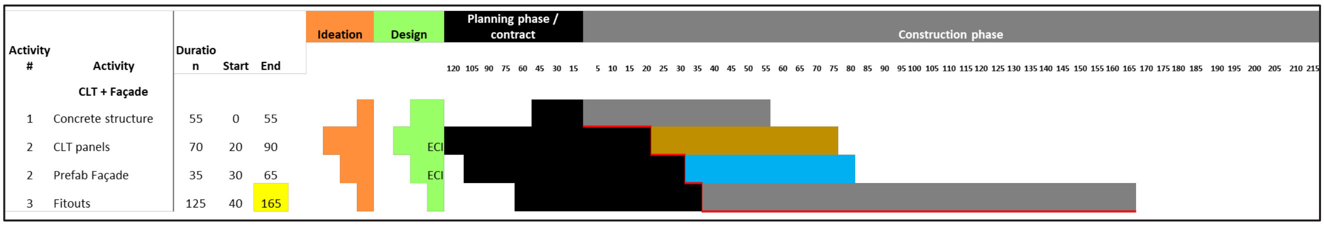


Figure 18 Project schedule for case 3

The case 3 schedule differs from the case 2 schedule in that it involves prefabricated façade erection and installation (shown in blue) that starts after formwork stripping is completed.

[31] Gasparri, E., Lucchini, A., Mantegazza, G. and Mazzucchelli, E.S., 2015. Construction management for tall CLT buildings: From partial to total prefabrication of façade elements. Wood Material Science & Engineering, 10(3), pp.256-275.

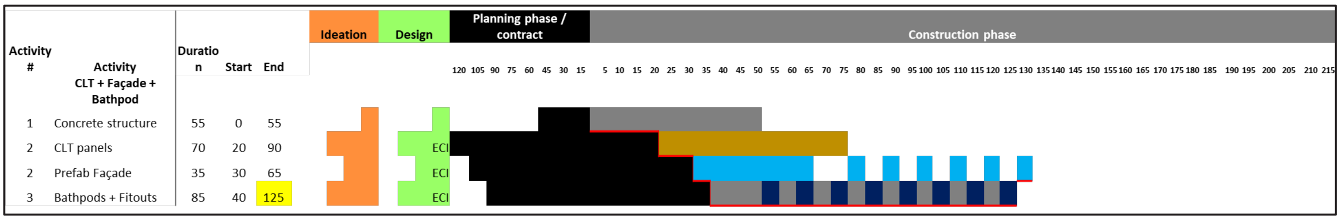


Figure 19 Project schedule for case 4

The case 4 schedule involves prefabricated bathroom pods that replace some of the wet trade activities involved on-site and save a considerable amount of site space, labour hours, and material handling requirements. We assumed assembly of bathroom pods and the superstructure happened horizontally; i.e. the superstructure is ready by the time the bathroom pods are scheduled to arrive. The bathroom pods are then lifted to their designated levels and slid horizontally to their final position. Façade installation on each level will be completed only after all bathroom pods are in place on that level. The scheduled arrivals and installations of the bathroom pods are indicatively marked in Figure 19.

2.2.4 Risk parameters

To compare the construction schedules of the proposed structures (see Figure 15), we developed a common set of risk parameters adhering to the SD approach. We prepared a list of system-level parameters common to each case of construction, based on a comprehensive literature survey of risks involved in constructing productised buildings (Figure 20). The parameters are grouped under 4 sections:

1. **Inefficiencies/defects/damages**: system-level events and circumstances that take place before the product arrives on the construction site that may significantly affect the construction schedule.[32] The parameters are further grouped as:
   a. Design:

      Involves design changes and inefficacies arising due to incompetent design. The risk associated with design changes is assumed to increase linearly with increasing productisation.[33] The impact of design uncertainties for conventional structure (case 1) is benchmarked at 1.

      The impact on the project schedule due to increasing productisation (from case 2 to case 4) is assigned an increasingly higher value as can be seen in Figure 20.

   b. Manufacturing:

      Involves manufacturing defects and defaults on the manufacturer's part in the production phase.[34]

[32] Yu, T., Man, Q., Wang, Y., Shen, G.Q., Hong, J., Zhang, J. and Zhong, J., 2019. Evaluating different stakeholder impacts on the occurrence of quality defects in offsite construction projects: A Bayesian-network-based model. Journal of Cleaner Production, 241, p.118390.
[33] Langston, C. and Zhang, W., 2021. DfMA: Towards an Integrated Strategy for a More Productive and Sustainable Construction Industry in Australia. Sustainability, 13(16), p.9219.
[34] Wuni, I.Y. and Shen, G.Q., 2021. Exploring the critical production risk factors for modular integrated construction projects. Journal of Facilities Management.

The impact of manufacturing uncertainties is assumed to be directly proportional to the level of productisation and assigned a number on a scale of 0 to 4.[35]

c. Damage during transportation and handling

Involves instances of structural damage to a prefabricated component during transportation, handling, and erection activities. Damage during this stage incurs time costs in retrofitting and delays the on-site assembly of that component and subsequent construction activities.

The impact of damage hazard is assumed to be directly proportional to the level of productisation and is assigned a number on a scale of 0 to 4.

d. Lack of coordination in teams

The time savings in OSM methods of construction can be quickly washed away due to a lack of coordination between teams. Inaccurate delivery times of the prefab components, incorrect planning and scheduling on the project manager's part, and insufficient provisions to receive the product on site can quickly have a cascading effect on the overall schedule.[36]

The impact of these parameters is assumed to be directly proportional to the level of productisation and is assigned a number on a scale of 0 to 4.

e. Inappropriate or insufficient clarity in risk/responsibilities allocation

OSM methods are not well understood by the entire construction industry value chain. Inefficiencies in addressing the risk allocation and responsibilities towards quality assurance and quality management mean some defects go unchecked/ unnoticed which can significantly delay construction.

As the likelihood of such events increases with the level of productisation, the impact of this parameter is assumed to be directly proportional to it and is assigned a number on a scale of 0 to 4.

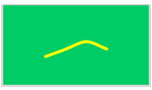
f. Lack of planning

OSM methods require a significant amount of upstream planning and coordination between the client, design, manufacturing, and procurement teams. Planning site activities and handling equipment and resources is vital to avoid assembly delays.[37]

The planning efforts are thought to be higher for a higher degree of productisation; i.e. higher levels of productisation are thought to naturally imbibe a culture of better planning

[35] Johnsson, H. and Meiling, J.H., 2009. Defects in offsite construction: timber module prefabrication. Construction management and economics, 27(7), pp.667-681.
[36] Wuni, I.Y. and Shen, G.Q., 2021. Exploring the critical success determinants for supply chain management in modular integrated construction projects. Smart and Sustainable Built Environment.
[37] Li, C.Z., Hong, J., Fan, C., Xu, X. and Shen, G.Q., 2018. Schedule delay analysis of prefabricated housing production: A hybrid dynamic approach. Journal of cleaner production, 195, pp.1533-1545.

from conception. Given this, the risk of planning uncertainty is assumed to climb from case 1 to case 3, and then gradually decrease with higher levels of productisation (to case 4).



g. Inexperienced staff for the chosen OSM methods

OSM methods require specialised skill sets that are unique to a building product being manufactured. Their site assembly and planning require specialised tools and equipment. Traditional labour without training is ill-equipped to handle the challenges in productised construction and can incur time delays.

Like the previous element, increasing levels of productisation are thought to bring in higher proportions of highly skilled workers, gradually increasing productivity. The impact of this uncertainty is assumed to decrease with the increasing levels of productisation.

h. Lack of data interoperability between available digital tools at various stages

The construction industry is a conglomeration of other industries and is dominated by small to medium enterprises (SMEs). Digital tools specific to individual SMEs may be vastly different across a project and may pose challenges in data portability. The project management software, resource management platform, communication medium, information transfer and sharing, and communication of the BIM[38] model may be hampered without standardised or compatible data management protocols. This issue may exacerbate the timely completion of several activities on site.

Including modern construction methods and OSM products in a project may simplify this process by reducing the number of SMEs and individual/independent contractors on site. Consolidating trades in a factory may alleviate this problem by delivering highly assembled units to the site. So, the uncertainties involved with data interoperability standards are assumed to increase from case 1 to case 2 and gradually decrease until case 4.

i. Inefficient systems integration to accommodate the change in construction schedule brought in by different levels of productisation

A productised construction project differs from conventional construction from conception.[39] Starting with the client, and ending with individual subcontractors, productisation needs increased involvement from all major stakeholders early. These interactions involve various paradigms of social systems, digital systems, managerial systems, and financial systems that also interact with each other.[40] These interactions can generate friction and delay decisions, or worse, create errors that go undetected until construction.

[38] Wu, H., Sun, C. and Li, T., 2014. Study on the Structure of a risk management framework based on BIM. In ICCREM 2014: Smart Construction and Management in the Context of New Technology (pp. 312-319).
[39] Wuni, I.Y., Shen, G.Q. and Antwi-Afari, M.F., 2021. Exploring the design risk factors for modular integrated construction projects. Construction Innovation.
[40] Xue, H., Zhang, S., Su, Y., Wu, Z. and Yang, R.J., 2018. Effect of stakeholder collaborative management on off-site construction cost performance. Journal of Cleaner Production, 184, pp.490-502.

System integration uncertainty is assumed to increase gradually from case 1 to case 3 until a certain proportion of productisation is reached, after which it decreases. That is, projects largely comprised of OSM products are based on improved understanding of the problem and include measures to avoid errors.

2. **Lead times:** Include the minimum level of lead times each system level activity may take depending on the product raw material,[41] size, shape, volume of units, weight, and transport logistics.[42]

   The design lead time, manufacturing lead time, delivery lead time, and planning lead time are assumed to increase gradually with increased levels of productisation and are assigned a number from 1 to 4.

3. **Logistics:** Include time delays incurred due to complexities in transportation and handling of OSM products, scheduling errors, and information mismanagement.

   a. Transportation delays

   These delays could result from multiple factors such as damage during transit, extreme weather, traffic congestion, regulatory requirements and restrictions, unavailability of a suitable vehicle, unsuitable road conditions, and so on. Since these factors are common to all forms of OSM products, their impact is assumed to increase gradually with increased levels of productisation.

   b. Scheduling errors

   Scheduling errors could be a combination of factors such as: incompetent site management, accidental events, insufficient forecasting, extreme weather, and so on. The impact of these errors is assumed to increase up to a certain level of productisation and then decrease with a further productisation.

   c. Information and data

   Communication channels between the factory logistics operator, site coordinator, and main contractor are vital in scheduling the delivery of the product and preparing the site for its arrival. Inefficient communication channels can exacerbate the problem and delay activities. The impact of these errors is assumed to increase similar to scheduling errors but with a more significant effect on outcomes.

4. **Site issues**

[41] Kar, S. and Jha, K.N., 2021. Investigation into lead time of construction materials and influencing factors. Journal of Construction Engineering and Management, 147(3), p.04020177.

[42] Hofstadler, C. and Kummer, M., 2021. Influence of project lead time and construction time on project targets. In Chances and Risks in Construction Management and Economics (pp. 279-328). Springer, Cham.

Involve site congestion and storage issues, lack of specialised equipment, errors in crane scheduling, resource unavailability, product geometric tolerance issues, quality control and defects, and assembly delays.

The impact of lack of specialised equipment, crane time management errors,[43] and assembly delays are assumed to follow a similar trend. The uncertainties relating to these factors are assumed to increase up to a certain level (case 3) and then decrease productisation increases (case 4).

Opinions on the effectiveness of OSM products in alleviating site congestion issues are mixed. Sometimes, constrained construction sites may benefit from productisation;other time it may pose challenges to its adoption. Nevertheless, an increased proportion of highly pre-assembled products can significantly reduce on-site activities and resource requirements. So, the impact of their uncertainties are assumed to decrease as productisation increases.

Geometric tolerance errors and quality defects can seep through off-site manufacturing and delays on-site assembly.[44] These factors are common to OSM products so their impact is assumed to be directly proportional to the level of productisation.

[43] Hussein, M. and Zayed, T., 2021. Crane operations and planning in modular integrated construction: Mixed review of literature. Automation in Construction, 122, p.103466.

[44] Enshassi, M.S., Walbridge, S., West, J.S. and Haas, C.T., 2020. Probabilistic risk management framework for tolerance-related Issues in modularized projects: Local and global perspectives. ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, Part A: Civil Engineering, 6(1), p.04019022.

Parameters	Conventional Case 1	CLT Case 2	CLT, Façade Case 3	CLT, Façade, Bathpod Case 4	Trend
Inefficiencies/defects/damages					
Design	1	2	3	4	
Manufacturing	0	1	2	3	
Damage during tranport and handling	1	2	3	4	
Lack of coordination in teams	1	2	3	4	
Inappropriate allocation of risk/responsibilities	1	2	3	4	
Lack of planning	1	2	3	2	
Inexperienced staff for prefab methodology	1	4	3	2	
Lack of data interoperability and digital tools	1	3	3	2	
Inefficient systems integration	1	3	4	3	
Lead times					
Design lead time	1	2	3	4	
Manufacturing lead time	1	2	3	4	
Delivery time	1	2	3	4	
Planning lead time	1	2	3	4	
Logistics					
Tranportation delays	1	2	3	4	
Scheduling errors	1	2	3	2	
Information and data	1	3	4	3	
Site issues					
Site congestion & Storage constraints	4	3	2	2	
lack of specialised equipment	1	2	3	2	
Error in crane scheduling	1	2	3	2	
Resource unavailability	4	3	2	3	
Prefab product geometric misfit	1	2	3	4	
Prefab product quality retrofit	1	2	3	4	
Assembly & installation delays	1	2	3	2	

Figure 20 List of risk parameters and their indicative influence to the project risk profile for each case

2.2.5 PERT

PERT is a graphical representation of the dependency structure of activities in the Gantt chart with probabilistic times of completions. PERT relies on user information about a task's optimistic time of completion (A), mean time of completion (M) and pessimistic time of completion (B). Based on this 3-point input, PERT calculates the probabilistic time of completion of the activity based on the Beta curve (3-point estimation).

$$\mu_{PERT} = \frac{A + 4M + B}{6}$$

$$\sigma_{PERT} = \frac{(B - A)}{6}$$

Based on the critical paths of the case study projects (case 1 to case 4) and SD-led project risk parameters described in Figure 20, and we used PERT technique to calculate probabilistic times of completion of an individual block of work in the schedule and its impact on overall project completion time. The optimistic times of completion for an individual block of activities in the master schedule were based on the Fenner Hall, Kambri project case study provided by Lendlease. The pessimistic times of the master schedule activities were derived from the corresponding impact scores. To simplify the analysis, we assumed the risk impact score of 4 incurred a delay of 1 day at the construction site to rectify the error. This relationship is arbitrarily chosen to enable the calculations showing the trends in project-level outcomes. To summarise, the pessimistic times were calculated as follows:

$$PT = OT + 0.25 \times (Impact\ Score)$$

Appendix A contains the detailed calculations of individual activity duration on the critical path for all 4 cases.

2.3 Project findings and outcomes

The results for completion times and project complexity scores based on risk impact relationships stipulated in **Figure 20** are shown in **Figure 21**. First, time savings come at the expense of an increased project complexity score. The term 'project complexity' should be understood from the perspective of 'the level of attention required in this context'. If the risk assumptions as stipulated before are acceptable, then increasing levels of productisation can come with significantly higher complexity (more than twice).

Figure 22 plots the completion time of cases with the project reliability (probability of completion). The steepness of the completion-reliability curve denotes the project variance. Case 4 (which has the highest levels of productisation) has the highest level of project variance despite being the quickest. The high level of variance reflects the unreliability of a large number of variables that could derail the productised construction schedule.

The benefits of off-site construction can be realised only if the stakeholders and project partners are aware of the complexities involved and have control measures in place. Important steps that can improve understanding include the following:

1. Develop a DfMA-led design of buildings
2. Involve project parties such as the client, the head contractor, designers and manufacturers early.
3. Clearly communicate consistent and compatible data formats and standards.
4. Keep a lessons learnt register to build an experienced team of workers.

5. Augment top-down planning of the critical path method with a bottom-up last planner system, dynamic scheduling and process optimization.
6. Develop a system dynamic approach to the risks involved in the project based on product typology and understanding of the causal connection between different events during construction.

The proposed framework for time-risk quantification for productised construction is based on existing knowledge of activity completion times based on the Fenner Hall construction at Kambri, ANU. The inputs are subjective and can change from contractor to contractor depending on their expertise and capabilities. Several assumptions made when developing the proposed methodology aimed to simplify the risk assessment framework. The assumption may not necessarily be true in all cases and the readers should exercise caution while interpreting the output of the assessment.

Despite the limitations, the risk parameters and their influence on completion time were frequently reported in the literature. The growing consensus on the need for early collaboration, change management, systems integration, data interoperability, project scheduling, quality control, risk analysis, and dynamic scheduling validates our findings. The proposed framework could be extended to analyse cost implications, safety risk etc subject to data availability.

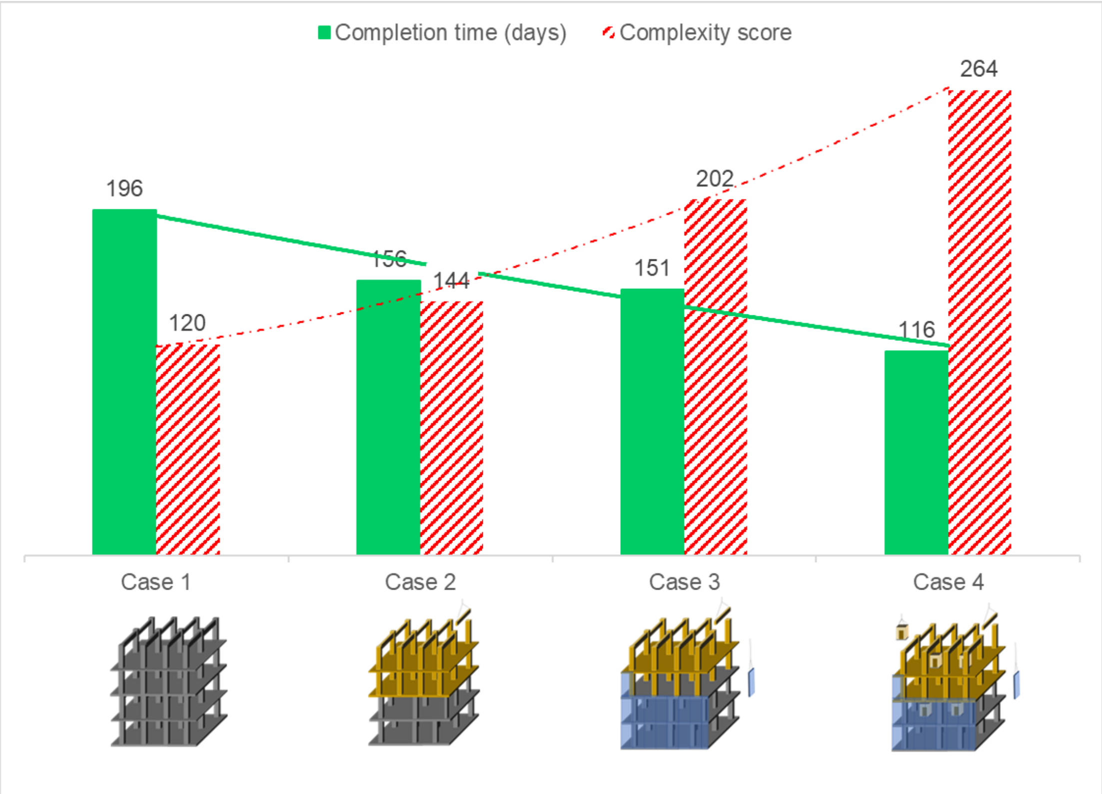


Figure 21 Project completion times with their complexity scores

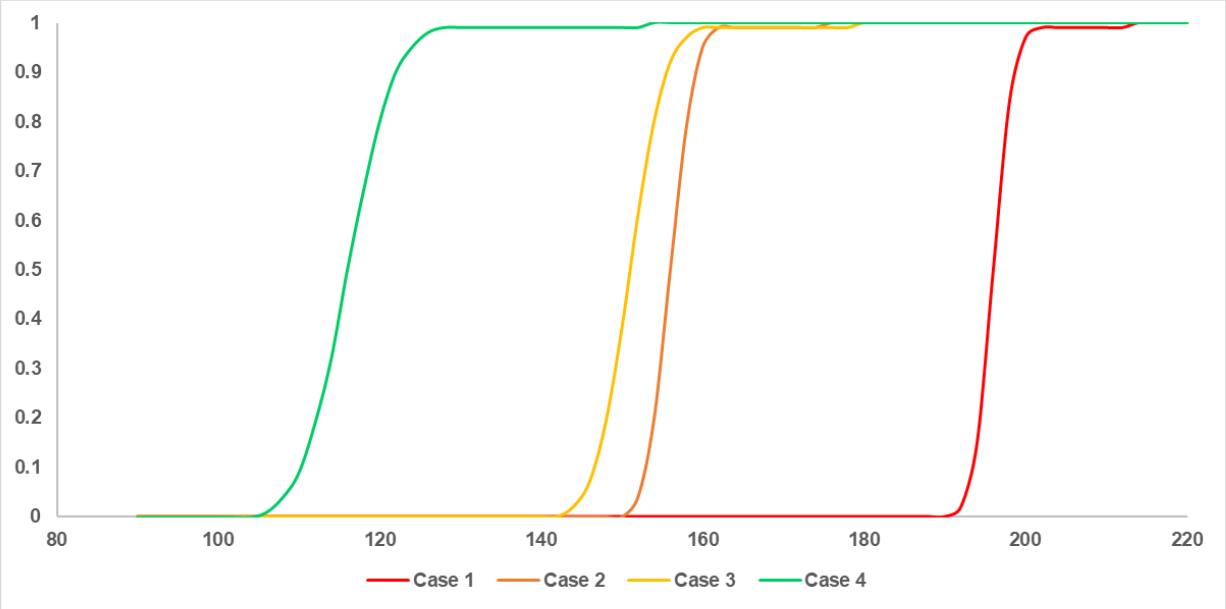


Figure 22 Project completion times with their probabilities of completion

CHAPTER 3 CONTENTS

CHAPTER 3: PRODUCTISATION CASE STUDY

Rebecca Williams, Dr Ivana Kuzmanovska, and Dr Duncan Maxwell

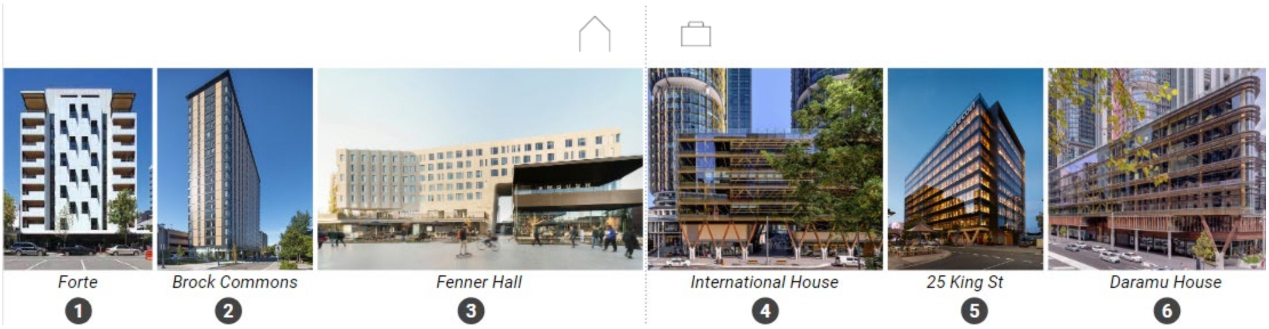


Figure 1. Case study projects.

3.1 Introduction

This chapter examines and analyses 6 case study projects (see Figure 1) to better understand the potential of a productised approach to building delivery. The buildings selected for study are:

1. *Forté Living* in Melbourne, Australia. This residential project is the first tall mass timber building to be constructed in Australia.
2. *Brock Commons Tallwood House* at the University of British Columbia in Vancouver, Canada. This student accommodation tower was, until recently, the tallest hybrid mass timber building in the world
3. *Fenner Hall* at the Australian National University in Canberra, Australia. This student accommodation building was one of a suite of prefabricated buildings delivered as part of the Kambri precinct project, the design for which developed through architectural competition.
4. *International House* in Sydney, Australia. This commercial mass timber building includes an innovative laminated veneer lumber (LVL) and Glulam composite beam (to achieve the large spans despite large service penetrations through the beams).
5. *25 King St* in Brisbane, Australia. This building is currently Australia's tallest and largest commercial mass timber building; however it will shortly be superseded as current projects under construction are completed.
6. *Daramu House* in Sydney, Australia. This is a commercial project, and sister building to [4] International House, with some amendments to structural grid and productisation approach.

Details about each case study project have been consolidated in Appendix A.

3.2 Aims, methods, and sources

This case study analysis was developed to provide a contextual background to the other streams of research in *Project #31 Critical Path Impact of Productisatio*n by examining current project delivery approaches using productised building elements. The analysis aimed to identify:

- the *degree of productisation* featured in each case study project
- productisation *drivers*
- productisation-related *successes*

- productisation-related *challenges* faced by the project teams
- the *risks* derived from the challenges faced.

For some of the case study projects ([1] Forté, [3] Fenner Hall, and [5] 25 King St), we were able to interview various members of the project teams (see Table 1). The interviews were conducted in a semi-structured format, guided by a list of questions (see Appendix B for an example) but also allowing for conversation to evolve organically. The remaining projects, for which interviews were not secured, were analysed using a range of project material provided by project stakeholders and published online. Table 2 presents the types of sources used for each building, and the bibliography at the end of the chapter contains the details of the sources.

Table 1. Interview details.

Project	Role (Company)	Title	Project team	Format
[1] Forté	*David Cracknell (Lendlease)*	Construction Manager	Building team	*1 x 60 min individual*
[3] Fenner Hall	*Architect (BVN)*	Principal Architect	Design team	*1 x 60 min individual*
[5] 25 King St	*Head Contractor (Lendlease)*	Construction Manager	Building team	*1 x 60 min individual*
		Project Manager	Building team	*1 x 60 min individual*
	Timber Delivery (DesignMake)	Senior Project Manager	Factory / site interface	*1 x 60 min individual*
		Principle Engineer	Structural/Design team	*1 x 60 min individual*
		Factory Manager	Manufacturing	*1 x 60 min individual*

Table 2. Types of sources used for each building in the case study.

Source	**[1]** Forté	**[2]** Brock Commons	**[3]** Fenner Hall	**[4]** International House	**[5]** 25 King St	**[6]** Daramu House
Company documents			2	1	1	1
Lessons learned					1	
Interviews	1		1		5	
Academic papers		2				
Media articles	5	4	2	1		
Stakeholder websites	1		1	1	1	1
External videos	1		1	2	1	1
Site observation		1				1

3.2.1 Limitations

Due to the difficulty in securing interviews and accessing project documents for all case studies, the source materials are unevenly distributed across the projects. Some of the analyses, such as [5] 25 King St and [6] Daramu House, benefit from a wealth of interview and observational data (respectively), and others, such as [2] Brock Commons, were described in depth through PhD dissertations and academic publications. However, for [4] International House, we could not access many primary data sources. So, the summaries are not comprehensive. Certain successes and risks may not be indicated for a given project, but this does not mean they were not experienced. Rather, they were not mentioned in any of the source material we gathered. Further interviews with key decision makers and contributors in the project teams of each project are necessary to develop the findings in more detail.

3.3 Project background

The industry partner on this project, Lendlease, was involved in 5 of the 6 selected buildings ([1] [3]–[6]) in varying roles including developer, designer, head contractor, or a combination of these (for details see Figure 2). Of these 5, the only project that Lendlease did not develop was [3] Fenner Hall. Lendlease's mass timber processing factory (DesignMake), which was launched in 2015, was involved in delivering mass timber components for [3] Fenner Hall, [5] 25 King St, and [6] Daramu House.

All 5 of the Lendlease buildings are located along Australia's east coast. The other project ([2] Brock Commons) is located in Vancouver. It was selected as an exemplar case for comparison due to its success in structural completion speed and integration of a Virtual Design and Construct approach. For this project, an external company built a digital twin using construction documentation, and consulted with the build team to ensure components and processes were both captured and sequenced properly. The team claims many issues were caught and ironed out during this process, and this approach greatly contributed to the success on site.

All case study buildings feature a concrete base (ranging from just foundations to a 2-storey concrete podium) supporting a mass timber structure, inherently productised in nature. The building selection represents an even mix of commercial and residential program (see Figure 3), in which a range of structural strategies are present:

- honeycomb wall and floor structure ([1] Forté and [3] Fenner Hall)
- post and beam ([4] International House, [5] 25 King St, and [6] Daramu House)
- post and slab ([2] Brock Commons).

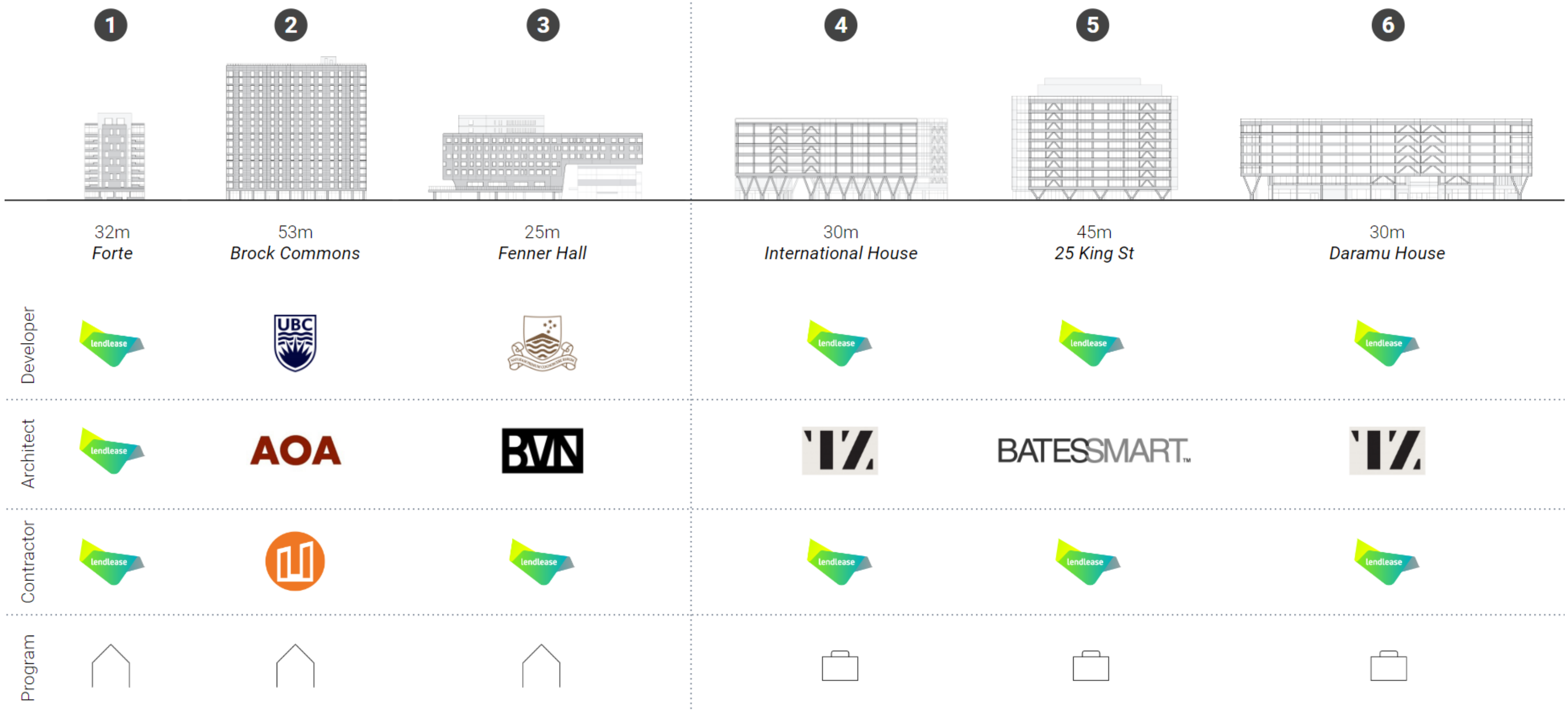


Figure 2. Case study building elevations and project team information.

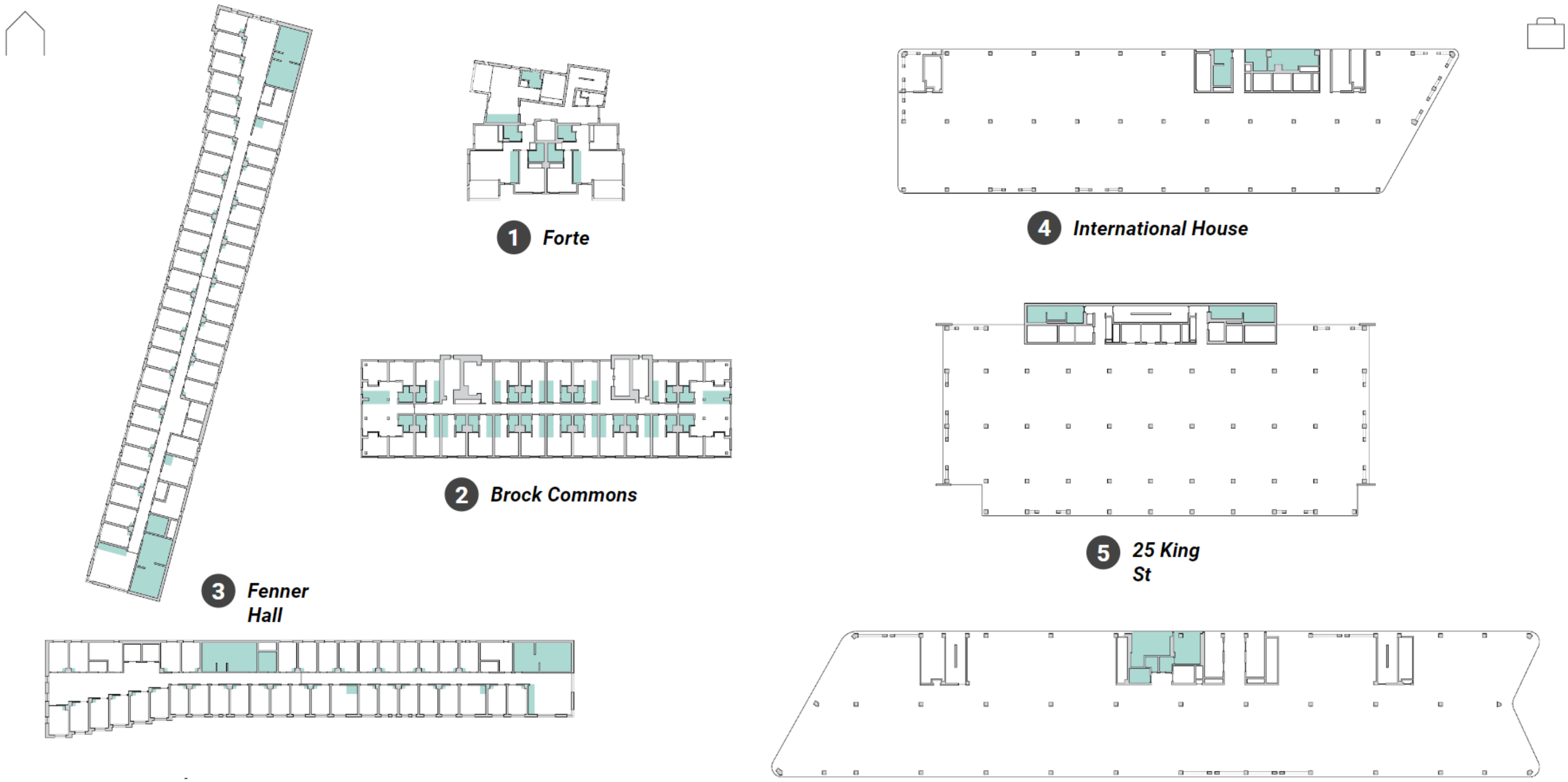


Figure 3. Case study building plans. Wet areas indicated in blue.

Figure 4 depicts the chronological timeline of the case study projects. While [1] Forté was completed much earlier, the remaining projects were, for the most part, constructed concurrently. Because the relatively small DesignMake team was responsible for engineering and delivering the mass timber components for 3 projects, tacit learnings were carried over between projects.

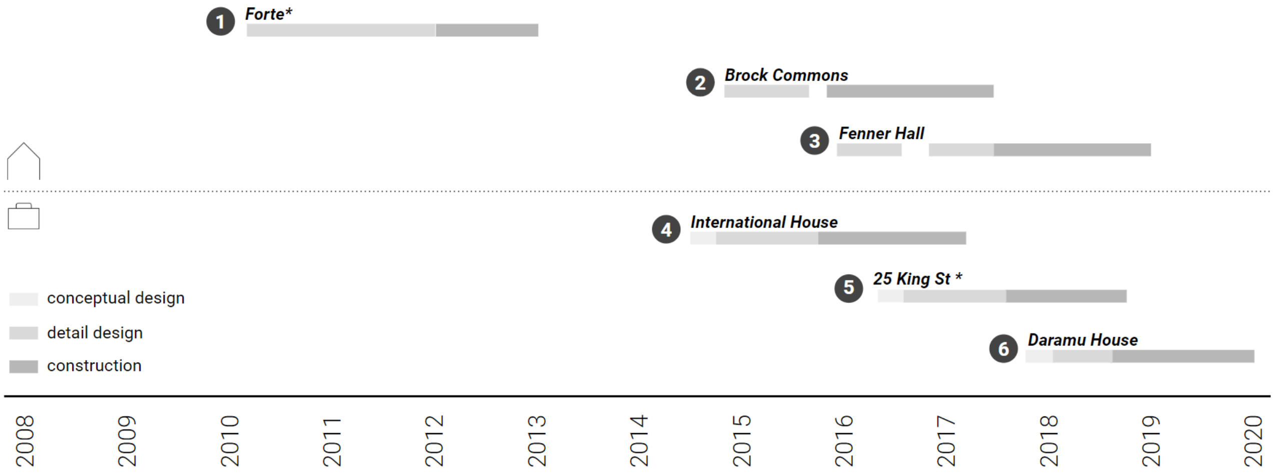


Figure 4. Chronological timeline of the 6 case study buildings.

3.4 Productisation

3.4.1 Key drivers

The key drivers for adopting a productised approach varied across the case studies. The most commonly cited reasons were related to the material benefits of mass timber, rather than those directly stemming from productisation itself (see Table 3). As might be expected, speed was also a key driver for using prefabricated elements. Interestingly, early aesthetic decisions (use of brick for 'timeless elegance') in the competition design of [3] Fenner Hall forced the development a special prefabricated CLT-brick slip system to achieve the necessary aesthetic without rely on in-situ bricklaying. Even if there were enough skilled bricklayers in the local area, the facade could not be completed in time for semester start if constructed in the conventional site-based way.

A motivation unique to the Lendlease buildings was their capacity to complete the prefabrication inhouse through DesignMake. Though not mentioned in any of the source material, one can infer the link to DesignMake may have been a key incentive to adopt mass timber, and therefore a productised approach on all projects delivered after the factory was set up.

Table 3: Motivations behind delivery methodology.

Motivations	[1]	[2]	[3]	[4]	[5]	[6]
Material-focus - sustainability credentials	+	+	+	+	+	+
- innovation = increases in property value	+	+	+			
- lightweight	+					
- government grant incentives		+				
Speed of construction		+	+	+		
Lendlease capacity in DesignMake				+	+	+

3.4.2 Degree of productisation

The productisation categories were informed by Bertram et al. 2019 (see Figure 5). In this approach, scale (x axis) and complexity (y axis) define the different classification levels of prefabricated elements. Complexity includes the number of different material types and components used, as well as the number and nature of factory processes, which inevitably affect the volume of work required to install and 'finish' the element on site. Generally speaking, as element complexity increases, the factory-to-site ratio is more heavily weighted towards factory work, reducing the intensity and duration of site work associated with that element.

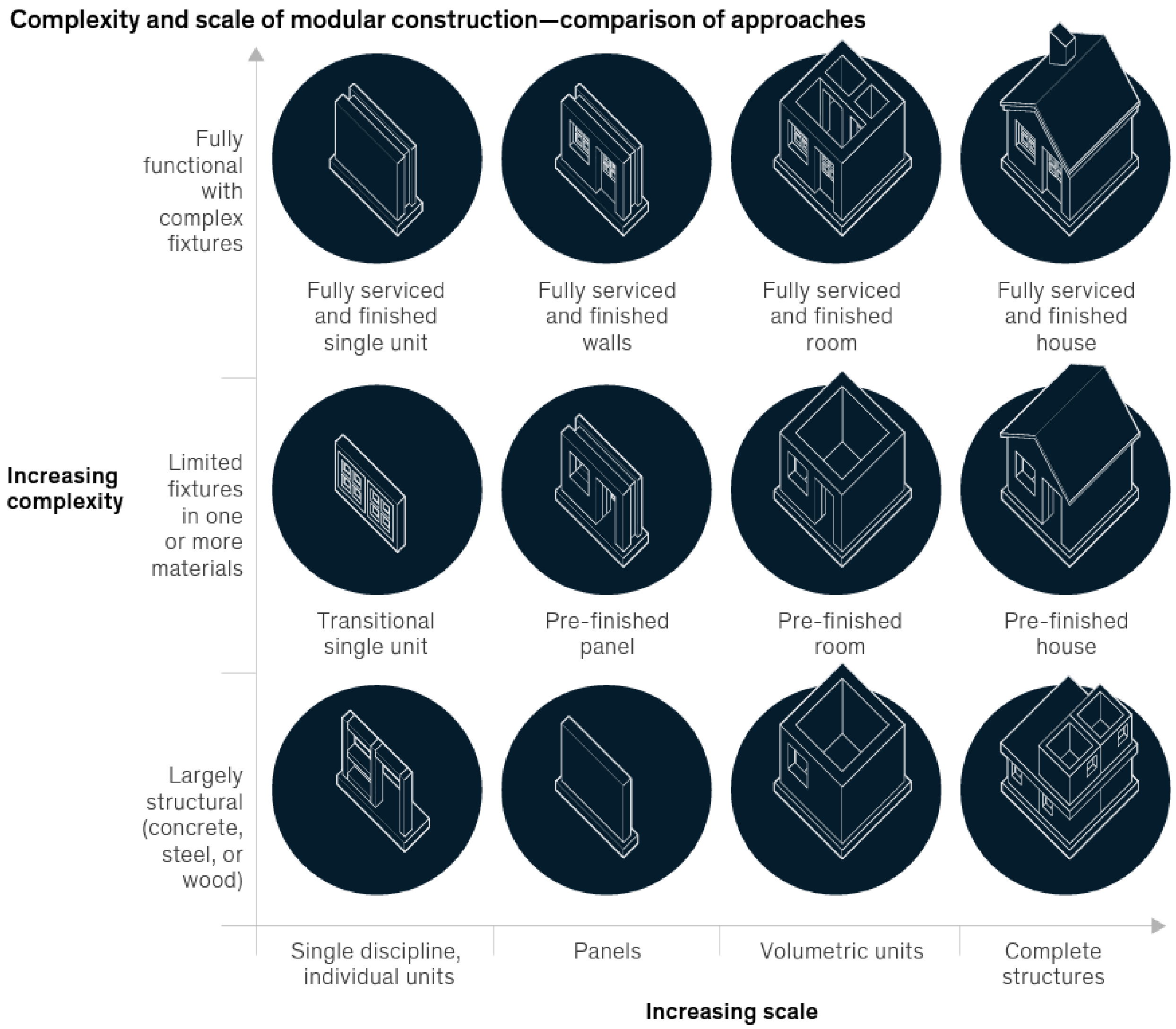


Figure 5: Assessing element complexity, diagram from Bertram et al. 2019.

As depicted in Figure 6, each case study used a different combination of prefabricated elements. The commercial buildings tended to have a wider variety of prefabricated element types, incorporating linear (columns and beams), planar (wall and floor panels or assemblies, framed bracing elements) and volumetric elements (lift cores, services risers, plant skids, bathroom pods), while each residential building included only 3 different element types. CLT slabs were used on every project, and prefabricated facades on all projects except one ([1] Forté). Consequently, the vapour membrane and facade were installed in-situ on that project, and this process was considered difficult. Volumetric prefabricated parts were the least utilised across all projects. On [1] Forté, using bathroom pods was described as positive and seen as successful.

Increasing scale and complexity

Building	*linear*		*planar*					*volumetric*		
	Columns	**Beams**	**CLT Walls**	**CLT Slab**	**Floor Assembly**	**K Brace**	**Facade**	**Lift Core**	**Services / Plant**	**Bath Pods**
1 Forte			x	x						x
2 Brock Commons	x			x			x			
3 Fenner Hall			x	x			x			
4 International House	x	x		x		x*	x	x*		
5 25 King St	x	x	x	x		x	x	x*	x	
6 Daramu House	x	x	x	x	x	x	x		x	

** pre-assembled on site, not in a factory*

Table 6: Prefabricated element types in each case study building.

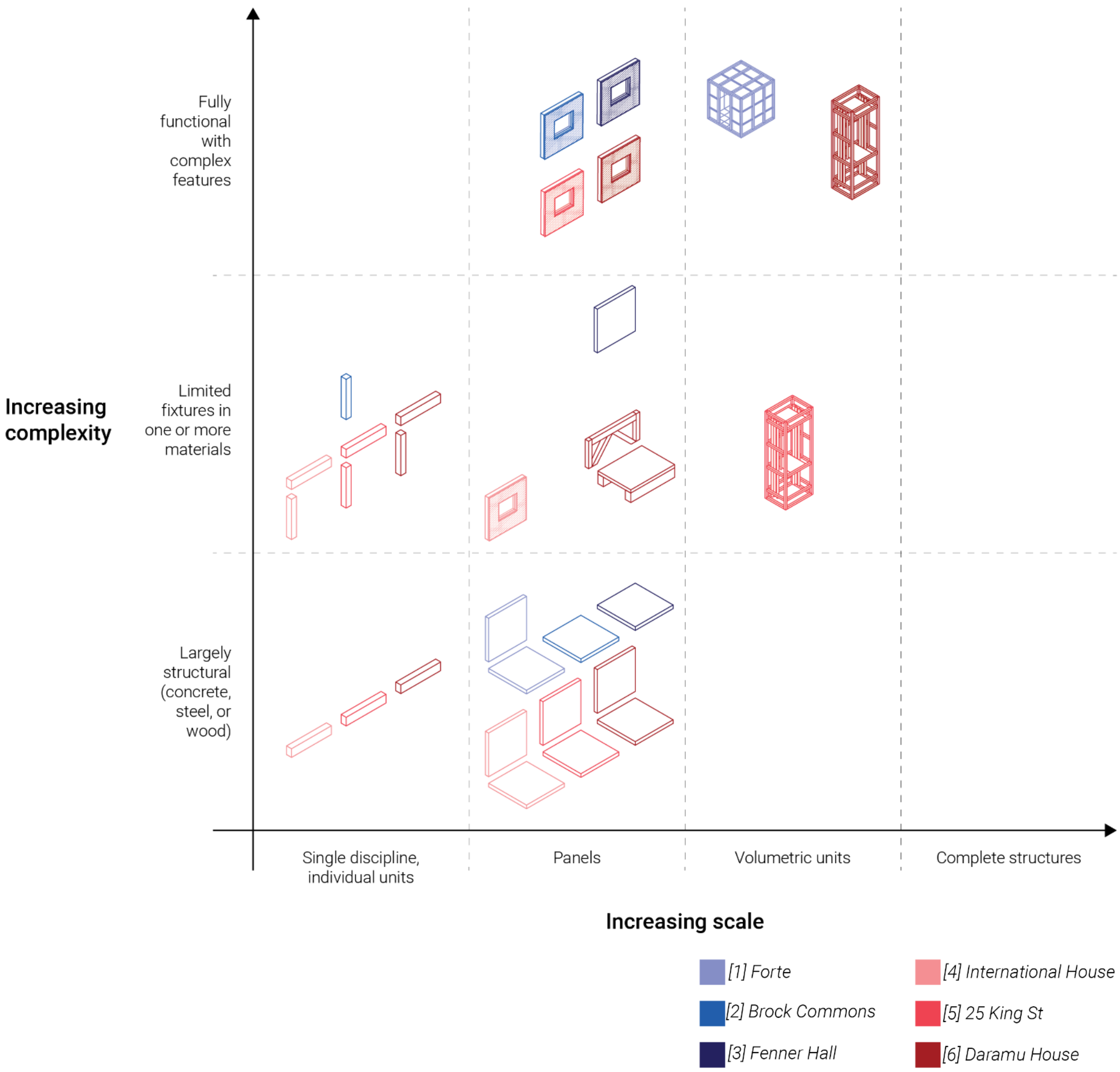


Figure 7. Productisation of case study buildings mapped according to spectrum defined by Bertram et al. 2019.

While complexity is considered between element types, it is not assessed within element categories in Figure 6. For example, [6] Daramu House contained both simple and complex columns and beams. The simple components were simply machined to the correct geometry. The complex elements contained additional steel connectors that were pre-fixed off-site. This spectrum of complexity begins to emerge in Figure 7, adopted from Bertram et al. 2019. The cluster of elements at the bottom left indicates most projects did not incorporate many prefabricated elements with high degrees of complexity and finish, rather opting for relatively simple structural components. The exception is incorporating finished facade elements.

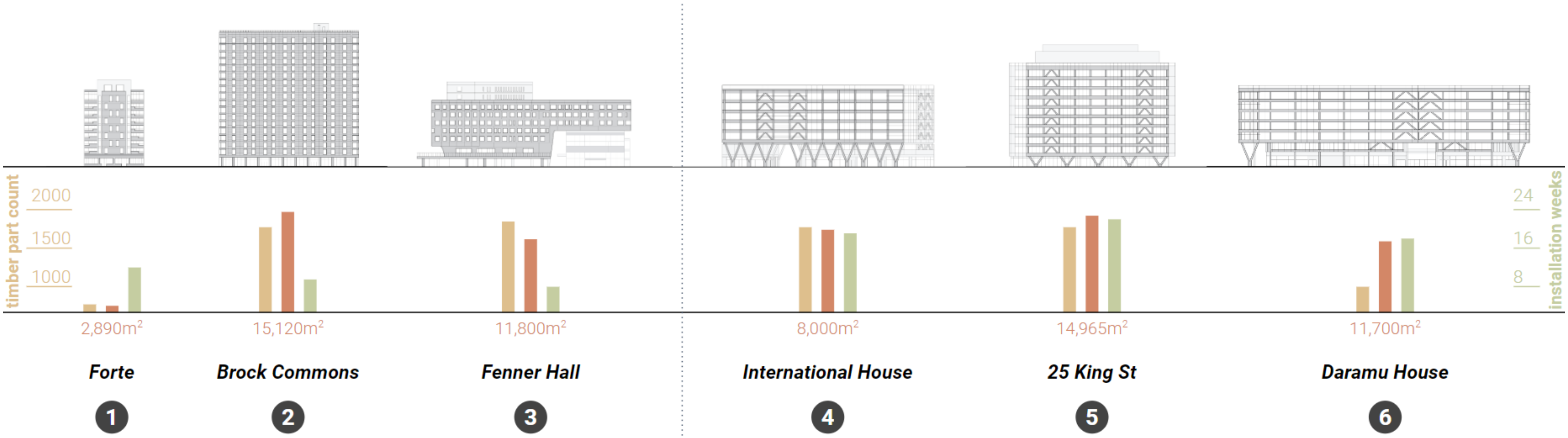
3.5 Successes

Table 4 presents project successes. Across the 6 projects, the most commonly cited success was related to the recognition and accolades awarded to the project, largely due to the novelty of mass timber and its sustainability credentials (see Appendix C for award details). The ‘green’ angle of the structural material tends to drive a broader sustainability agenda within such projects, demonstrated by their high green star ratings (5 green stars: [1] Forté; 6 green stars: [4] International House, [5] 25 King St, and [6] Daramu House), and additional features such as solar panels ([4] International House and [6] Daramu House) and green roof ([6] Daramu House).

The ability to eliminate scaffolding, reduce labour requirements, and increase the speed and safety of the construction program were also seen as key successes, however it is unclear whether project teams quantified the latter claims.

Table 4: Project successes

Successes	[1]	[2]	[3]	[4]	[5]	[6]
Project recognition/awards	+	+	+	+	+	+
No scaffolding		+	+	+	+	+
Reduced labour		+	+	+	+	
Speed	+	+	+		+	
Safety	+			+	+	+
Efficient sequencing		+			+	
Certainty of delivery		+			+	
Waste reduction			+		+	
Clean site		+			+	
Positive reception within the workforce	+	+				
Quiet site	+					
Tightly controlled tolerances, very little rework required		+				
Integrated design process		+				
1:1 prototype		+				



UPDATE

Building	Floor area (m²)		Construction time (months)		Construction Time / Floor Area		Structural time / floor area		Structure as % of build	# Structural parts		Parts per GFA	
	actual	rank	actual	rank	actual	rank	actual	rank	actual	actual	rank	actual	rank
1 Forte	2,890	6	10	1	0.104	6	0.029	6	30	759	1	0.26	6
2 Brock Commons	15,120	1	18	6	0.036	1	0.004	1	13	1762	6	0.12	2
3 Fenner Hall	11,800	2	15	4	0.038	2	0.005	1	13	1839	6	0.16	3
4 International House	8,000	4	14	4	0.053	3	0.017	3	34	1740	6	0.22	5
5 25 King	14,965	1	15	4	0.030	1	0.010	2	37	1764	6	0.12	2
6 Daramu House	11,700	2	13	3	0.033	1	0.011	2	35	1000	2	0.09	1

Figure 8: Construction times and part count.

3.5.1 Comparative analysis

We considered the following criteria to understand how the projects performed in relation to one another:

- total construction time (months) / floor area (m^2)
- structural completion time (months) / floor area (m^2)
- structural completion time as a % of total construction time
- number of structural parts / floor area (m^2)

Normalised ranks were given to each project for each criterion.

Figure 8 presents the data for each project. This data was extracted from the sources available, and in some instances, inferred. The following complexities were not captured:

- At structural completion, not all buildings were similarly complete. For example, [1] Forté was the only project to use bathroom pods. The installation methodology (bathroom pods installed in tandem with structure: floor, pod, floor) meant at structural completion, the bathrooms were completely finished. This was not the case with the remaining buildings.
- Construction time data does not account for the number of installers present on site, nor the number of working days per week (5, 6, 7?), and whether this was consistent across the project.
- The analysis does not account for the variation in design complexity. For example, the number and size of wet areas varies greatly across the projects. As shown in Figure 3, the residential projects have much smaller, but many more bathroom / laundry / kitchen zones. The commercial projects tend to consolidate the wet areas for each floor in one larger zone. Further, although the commercial projects have fewer internal walls, the services for all 3 commercial projects were installed directly beneath the soffit and exposed, requiring a higher standard of workmanship than is necessary for concealed services.

3.6 Challenges and risks

Project challenges were consolidated and collated in Table 5, grouped according to 3 key subcategories informed by important phases in the project delivery cycle: design; manufacture and delivery; and site.

Table 6 presents the potential risks of a productised approach to building design and delivery, relating to to the same 3 subcategories: design; manufacture and delivery; and site.

Table 5: Challenges arising from the productised approach.

Design challenges	[1]	[2]	[3]	[4]	[5]	[6]
Approvals-related processes and procedures take time and cost money	+	+	+		+	
Need for front-loaded design process and early design freeze			+		+	+
Fragmented design to manufacture workflows			+		+	
Product lead time compressing design time					+	
Contractual arrangements prohibitive of early collaboration with stakeholders					+	
Manufacture and delivery challenges	**[1]**	**[2]**	**[3]**	**[4]**	**[5]**	**[6]**
Parts delivered to site with defects			+		+	+
Pre-finished elements (or elements with visible finish) being damaged				+	+	+
Poor delivery QA (parts missing from truck, improper stacking on truck)					+	+
Parts not designed with manufacturing and QA checks in mind					+	
Manufacturing delay					+	
Site challenges	**[1]**	**[2]**	**[3]**	**[4]**	**[5]**	**[6]**
Water ingress through module joins causing damage of finished surfaces	+	+		+	+	+
Inexperience of workforce due to novelty of materials or methodology		+			+	+
Space constraints on site, little room for part storage		+		+		+
Crane capacity		+		+	+	
Connections not designed with accessibility in mind	+			+		+
Wind		+		+		
Incorrect sequencing	+	+				
Sequencing domino effect	+					+
Incompatibility between site and factory tolerances					+	+
Delivery bay blockage due to install problems			+			+
Too many components, driven by structural design	+					

Table 6: Risks distilled from challenges experienced on case study projects.

Design risks
Interface issues and inefficiencies caused by different design timelines for productised and non-productised elements
Interface issues and inefficiencies caused by inability to incorporate expert product knowledge prior to design freeze
Delays and cost overruns caused by unforeseen testing of Deemed to Satisfy solutions for new materials and methods
Manufacture and delivery risks
Delay to production schedule due to need for design rework
Delay to production and/or installation schedule due to poor QA and defect / damage rectification
Delay to installation schedule due to disrupted site deliveries
Site risks
Potential for errors due to the team learning process
Delivery coordination issues caused by misaligned site and delivery schedules
Slowed program due to reliance on crane for most installation activities
Potential delay to schedule and unnecessary non-value add work using the crane for out-of-sequence deliveries
Delay due to assembly difficulty of connection design
Safety risk due to assembly difficulty of connection design

3.7 Conclusions and future research opportunities

This analysis examined 6 mass timber building projects to better understand the different ways that a productised approach to building delivery can play out, and their associated pros and cons. The study identified the nature and degree of productisation adopted in each project, as well as the motivations to use a productised approach. Successes and challenges related to the productised approach were identified, as well as the resulting risks, to be considered in future projects. In total, we identified 14 successes and 21 challenges. These informed the distillation of 12 potential risks related to a productised approach to building delivery.

Our main findings are as follows:

- In general, the decision to adopt a productised approach was largely driven by the beneficial properties of mass timber as a building material, with the potential for construction speed gains providing an added bonus. This is reflected in the nature and degree of productisation adopted in these projects, which (apart from prefabricated facades) tend to sit on the lower complexity end of the spectrum, with lower degrees of finish.
- Other than the industry awards and recognition achieved by the use of mass timber as a structural material, reduced labour, speed, safety, and need for scaffolding were considered to be the main successes of the productised mass timber approach.
- On the other hand, the productisation-related challenges ranged from design-focused issues such as the need for approvals and design freezes, to poor QA during manufacturing and delivery, and water ingress and inexperience of workforce at the site.

- Many of the challenges point to risks that can ultimately result in schedule delays and cost overruns, and are therefore important to consider and address early on.
- Significant benefits are to be gained from properly implementing DfMA and quality management processes, and these should be factored into planning processes.

As this study was conducted using limited primary data, further research should seek to verify our findings with the relevant project teams, and expand the conversations around decision making in such projects along the following questions:

1. Who makes the decisions to adopt a productised approach in large scale projects such as those selected for case study?
2. How are decisions about degree and nature of productisation made (using what information/data), and when?
3. How might the non-productised elements of the building design and delivery be reconsidered / redesigned / restructured to strengthen the potential speed gains?

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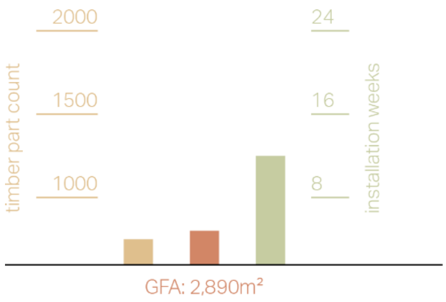
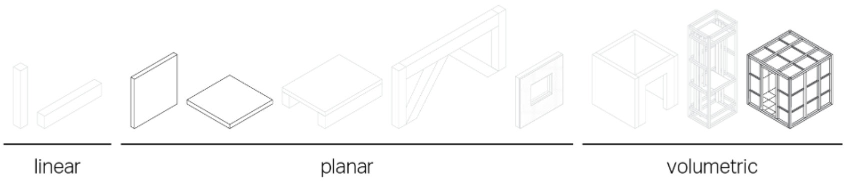
Appendix A. [1] Forté Living

Project Timeline

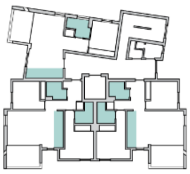


Structural Installation



Productisation

Typical Floor Plan

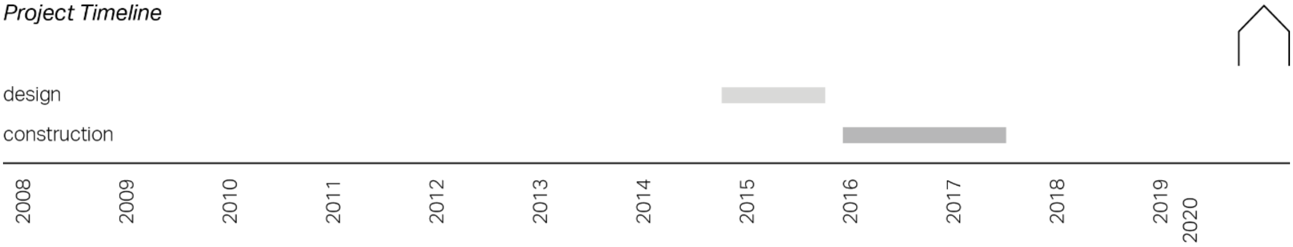


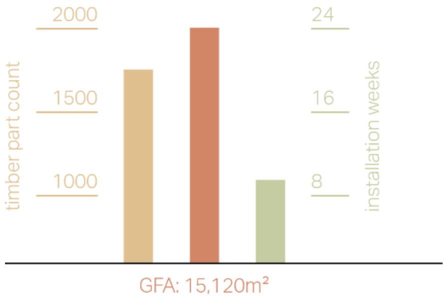
Street Elevation

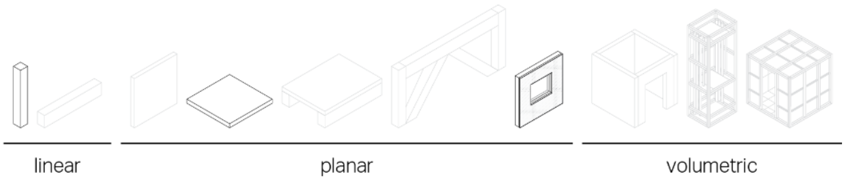
Forté Living is a 10-storey CLT apartment building completed in Melbourne in 2012. Lendlease was the developer, architect, and head contractor. Forte was Australia's first CLT building, and the world's tallest CLT building at the time of completion. The 759 CLT panels that comprise the honeycomb structure were harvested and manufactured in Austria and shipped to Australia in 25 containers. CLT walls and soffits are exposed in certain parts of the building.

Appendix A. [2] Brock Commons Tallwood House

Project Timeline



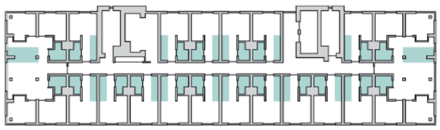




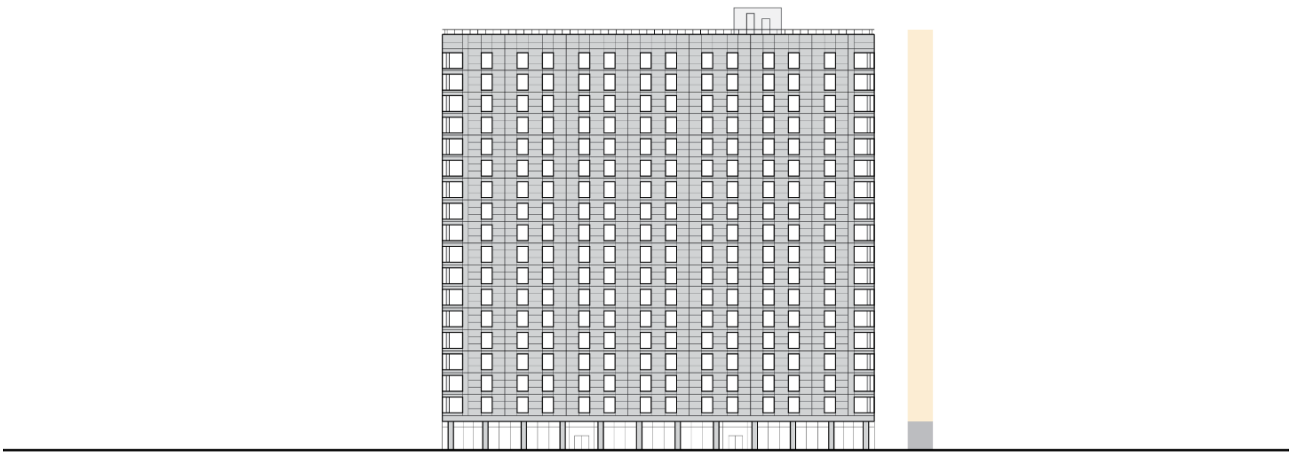
Structural Installation

Productisation

Typical Floor Plan (wet areas)



North Elevation (timber and concrete levels)

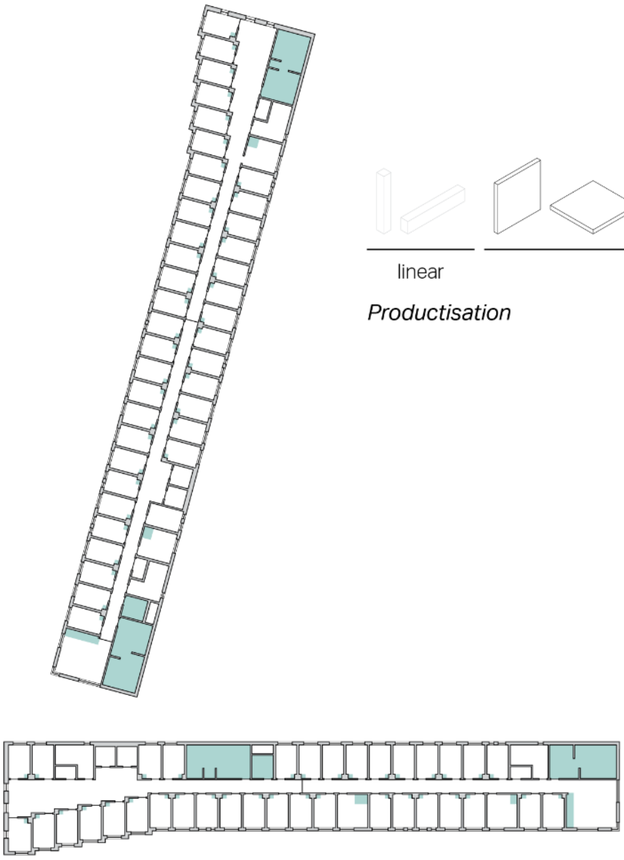


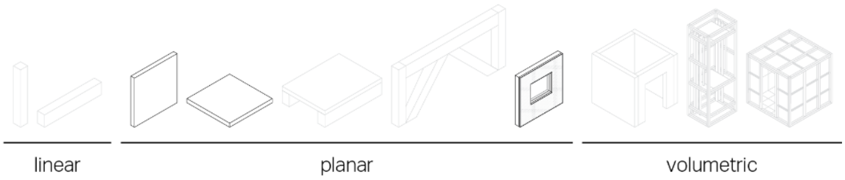
Brock Commons Tallwood House is an 18-storey student accommodation tower located on the University of British Columbia campus in Vancouver. The hybrid building structure features an in-situ concrete core, and CLT floors supported by Glulam columns so slender that they could be installed by workers without a crane. A special steel column-to-slab-to-column connection detail was developed to ensure ease and speed of assembly. A key feature was using a comprehensive Virtual Design and Construct process to ensure smooth project delivery.

Appendix A. [3] Fenner Hall

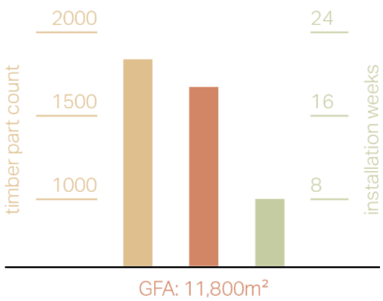
Project Timeline

Typical Floor Plan (wet areas)



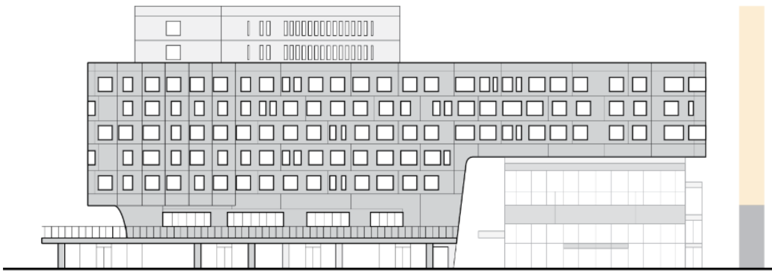


Productisation



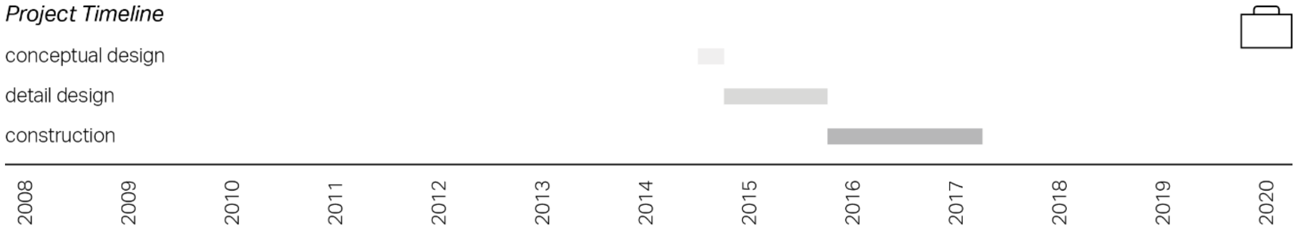
Structural Installation

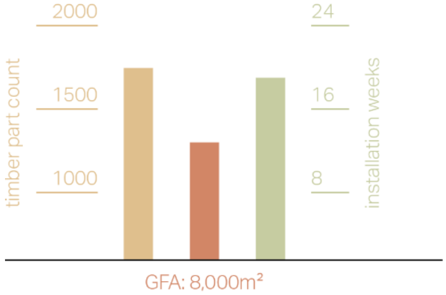
South West Elevation (timber and concrete levels)



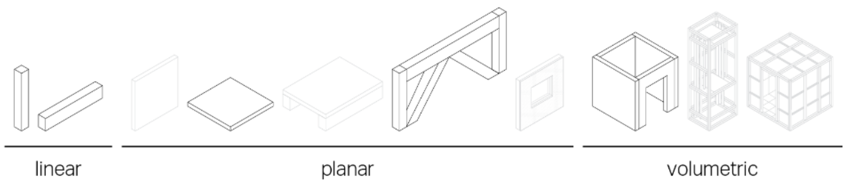
Fenner Hall is a 9-storey student accommodation building situated in the Kambri precinct of the Australian National University in Canberra. BVN won an architectural competition to design the whole precinct, and later collaborated with Lendlease to deliver the precinct using a mix of in-situ construction, mass timber components processed by DesignMake, precast elements, and prefabricated assemblies such as the Fenner Hall facades. The prefabricated facade system developed for the project incorporates brick slips to achieve a masonry aesthetic.

Appendix A. [4] International House



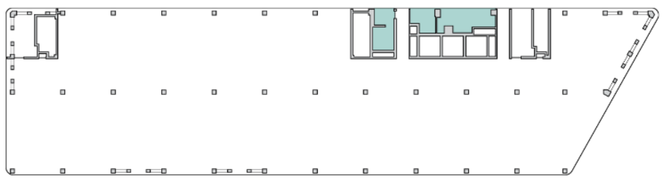


Structural Installation

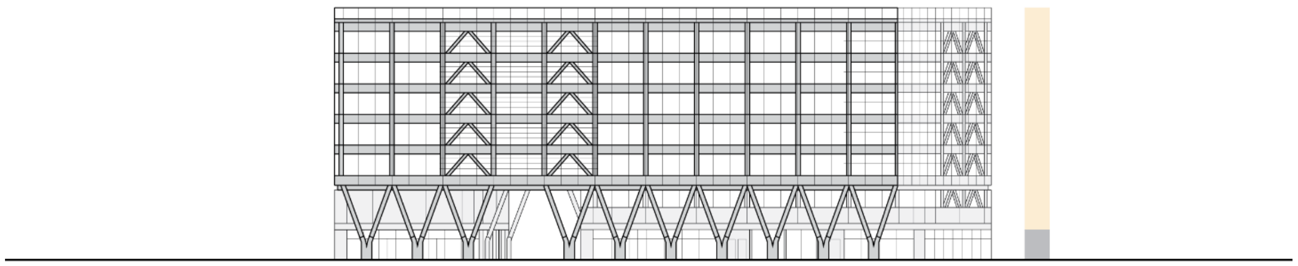


Productisation

Typical Floor Plan (wet areas)



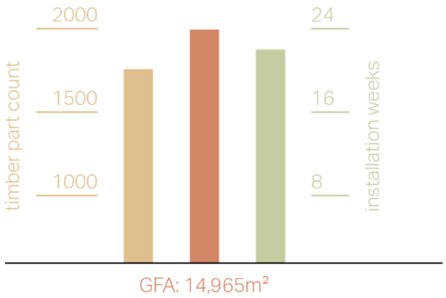
East Elevation (timber and concrete levels)



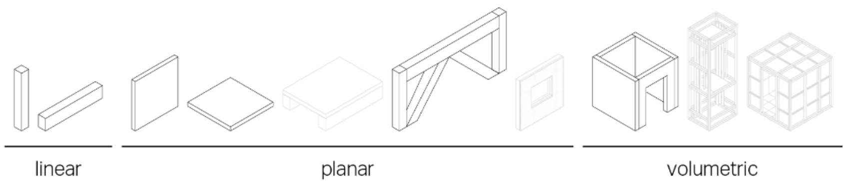
International House is a 7-storey office building located in Sydney, and completed in 2017. It was the first of 2 sister buildings designed by Tzannes for the Barangaroo precinct. To achieve the necessary large services penetrations through the 9.5 m primary beam spans, a novel composite spruce and beech beam was developed in collaboration with Hess. Two layers of LVL were sandwiched between Glulam outer and middle layers. The 9.5 x 6 m grid and overall structural design in this project was further refined in the Daramu House project.

Appendix A. [5] 25 King St

Project Timeline

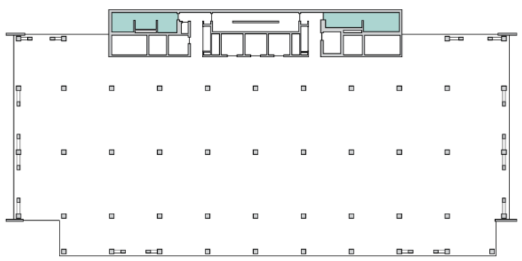


Structural Installation

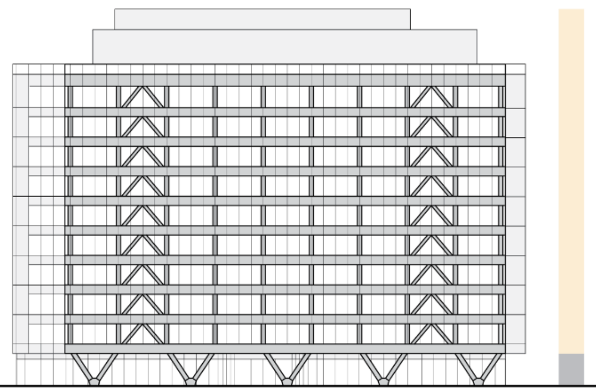


Productisation

Typical Floor Plan (wet areas)



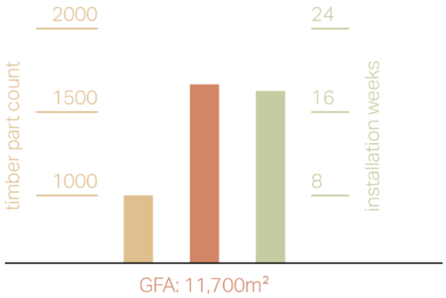
South Elevation (timber and concrete levels)



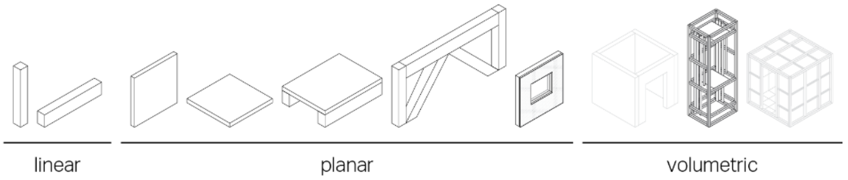
25 King St is a 10-storey commercial building set in the Brisbane Showgrounds, designed by Bates Smart and developed and constructed by Lendlease using DesignMake timber elements. It features a Glulam column and beam structure with a CLT structural core and floors. The structural installation involved on-site pre-assembly of lift cores (using a jig) and bracing elements.

Appendix A. [6] Daramu House

Project Timeline



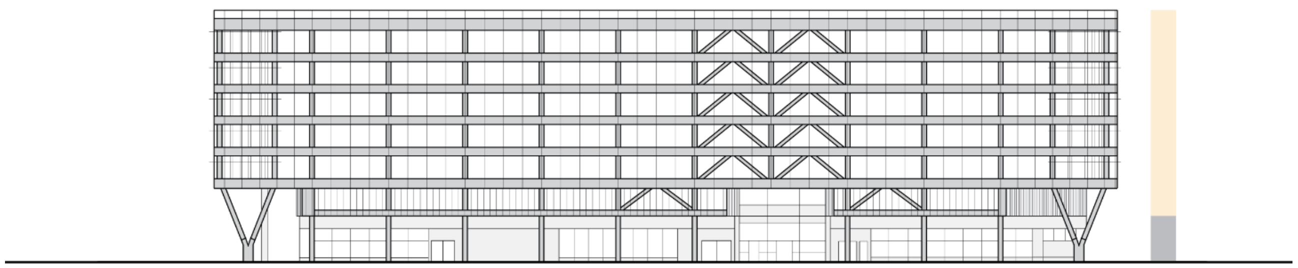
Structural Installation



Productisation

Typical Floor Plan (wet areas)

East Elevation (timber and concrete levels)



Daramu House is the 7-storey sister building to International House, designed by Tzannes and developed and delivered by Lendlease. DesignMake designed and produced the mass timber elements, and certain changes were made based on learnings from International House and 25 King St. The large (9 x 9 m) structural grid in this building was achieved by using a 2-way beam and slab system, for which prefabricated floor assemblies called rib-decks were developed (containing a CLT slab supported on long edges by 2 Glulam beams).

Appendix B

Semi-structured interview questions for BVN Architect team of [3] Fenner Hall

1. How long have you been working in the building industry?
2. Can you please describe your experience with off-site manufacturing in building projects?
3. Please briefly describe your role in / involvement with the Fenner Hall project.
4. Can you elaborate on the history of this project?
5. Which elements of the project were manufactured and / or pre-assembled off-site?
6. Who made the decision to use CLT and prefabrication on this project and when were these decisions made?
7. What were the key drivers behind the decision to productise and produce off-site?
8. Can you please talk about the specific events and processes that influenced the design and formal decision making with regards to the off-site manufactured parts on this project?
9. Did the use of CLT / prefabrication on this project change the typical nature and / or scope of your work? (risk management, cost structures, level of detail resolution, timelines)
10. How were digital technologies used to deliver the Fenner Hall project?
11. Were you involved in the scheduling process on this project? If yes, what did this process entail?
12. What information and / or assumptions were you working with when developing the design?
13. What challenges and / or barriers did you face in this project?
14. Are you familiar with the term ‘critical path’? If yes, what would you say were the key factors affecting the critical path on this project?
15. Are you familiar with the term ‘DfMA’? If yes, was DfMA incorporated into the design process of Fenner Hall? How?

Appendix C

Case study project awards

Project	Awards
[1] Forté	2014 Australian Property Institute (API) Environmental Excellence Award
[2] Brock Commons	2018 International Prize for Wood Architecture 2018 Lieutenant Governor of BC Award 2018 Sustainable Architecture & Building Green Award 2018 Canadian Wood Council Wood Works Architect Award 2018 Canadian Wood Council Wood Works Innovation Award 2018 Canadian Wood Council Wood Works Engineer Award 2018 Lieutenant Governor of BC Engineering Excellence Award 2018 Vancouver Regional Construction Association Award 2017 Premier's Innovation & Excellence Award 2017 Canadian Wood Council Special Jury Award 2017 Institution of Structural Engineers Innovation Award 2017 NCSEA Excellence in Structural Engineering Award 2017 Construction Dive Five Favourite Projects of the Year
[3] Kambri Precinct	2020 Australian Institute of Architects (RAIA) ACT Chapter Educational Architecture Award 2020 Australian Institute of Architecture (RAIA) ACT Chapter Derek Wrigley award for Sustainable Architecture 2020 Good Design Awards, Best in Class Accolade in Precinct Design 2020 Australian Institute of Architects (RAIA) ACT Chapter Urban Design Award 2020 IDEA Award Sustainability Award 2020 Australian Interior Design Awards Best of State Commercial Design 2020 Australian Institute of Architects (RAIA) ACT Chapter Public Architecture Award 2020 Australian Institute of Architects (RAIA) ACT Chapter Commendation Commercial Architecture 2019 Australian Timber Design Awards – Multi Residential Award Winner
[4] International House	2019 World Architecture Network – Commercial Project under 50,000sqm (Silver) Award 2019 World Architecture Network – Wood in Architecture (Silver) Award 2019 Property Council of Australia – Australian Development of the Year Award 2019 Property Council of Australia – Best Office Development in Australia Award 2019 Property Council of Australia – Rider Levett Bucknall NSW Development of the Year 2018 World Architecture Festival – Best Use of Certified Timber Award 2018 AIA National Award for Commercial Architecture 2018 AIA (NSW) Milo Dunphy Award for Sustainable Architecture 2018 AIA (NSW) Sir Arthur G. Stephenson Award for Commercial Architecture 2018 UDIA NSW Award for Excellence in Commercial Development 2018 Urban Taskforce Development Excellence Award 2018 Master Builders Association – Outstanding Construction Award 2018 Master Builders Association – Commercial Building up to $50M Award 2018 Master Builders Association – Innovation Award 2018 Master Builders Association – Excellence in Energy Efficiency Award 2018 Master Builders Association – Best Use of Timber Award 2017 Chicago Athenaeum and the European Centre for Architecture and Design - International Architecture Award 2017 Australian Timber Design Award – Excellence in Timber Design 2017 Australian Timber Design Award – Excellence Award for Public or Commercial Building 2017 Australian Timber Design Award – Excellence Award for Sustainability 2017 Australian Timber Design Award – Peoples' Choice
[5] 25 King St	2021 CTBUH Award of Excellence, Best Tall Building Under 100 Metres, Category Winner 2019 AIA (QLD) Architecture Awards, Beatrice Hutton Award for Commercial Architecture 2019 AIA (QLD) Architecture Awards, Harry Marks Award for Sustainable Architecture 2019 AIA National Architecture Awards, Sustainable Architecture Commendation
[6] Daramu House	2021 Green Good Design Award Architecture 2020 AIA (NSW) Architecture Award for Commercial Architecture 2020 AIA (NSW) Commendation for Sustainable Architecture 2020 AIA (National) Commendation for Commercial Architecture 2020 Australian Timber Design Award for Commercial Architecture

CHAPTER 4 CONTENTS

CHAPTER 4: AUTOMATED AND OPTIMISED DYNAMIC SCHEDULING FOR PRODUCTISED CONSTRUCTION

Songbo Hu, Yihai Fang, Robert Moehler

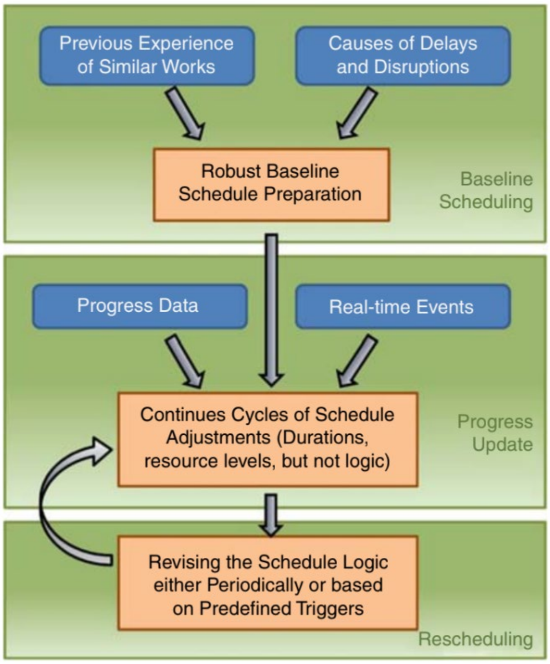


Figure 1. Predictive-reactive dynamic scheduling system Concept [3].

4.1 Introduction

This chapter delves into the examination and analysis of dynamic scheduling (DS), as depicted in Figure 1, to gain a deeper understanding of its potential to dynamically adjust building production processes and optimise resource utilisation and efficiency in building delivery. This section contextualises the concept, which is commonly used in manufacturing, for its application in the building delivery. The content is organised as follows:

- Conduct an extensive state-of-the-art review in construction scheduling, progress monitoring/tracking, and schedule adjustments, to address the fragmentation and lack of integration between DS and progress monitoring/tracking in the construction industry.
- Identify a standardised data structure for on-site activities and curate data from different information sources to bridge the gap between as-planned and as-is data at the activity level.
- Identify suitable ontological models of schedule, consisting of 6 elements, and utilise natural language processing and computer vision technologies to extract information from various databases and paper-based documents.
- Evaluate approaches for their potential to improve resource utilisation, efficiency, and knowledge accumulation within an organisation.

An extended list of concepts of this literature review were presented regularly at fortnightly conversations with industry partner liaisons, Karl-Heinz Weiss and Steven Huang, to capture and reflect on organisational knowledge and experiences.

4.2 What is dynamic scheduling (DS)?

Construction sites are dynamic in nature, and it is almost impossible to carry out pre-determined schedules precisely without adapting to actual progress.[1] Disruptive events (e.g., materials arriving late) constantly happen in real time, damaging schedules and potentially incurring delays and cost overruns. However, traditional scheduling methods for construction projects, such as the critical path method (CPM), analyse on-site activities statically and deterministically, and cannot accommodate and mitigate the impacts of real-time disruptive events.[2] Thus, construction schedules produced by these methods are often sub-optimal and ineffective in adapting to changes on site, which are neither optimised nor realistic.

DS is essential for successful project planning by absorbing the impact of real-time events, analysing the current schedule status, and modifying it with optimised measures to mitigate disruptions. DS, which has been extensively discussed in the manufacturing industry, is promising for improving both the realism and optimality of construction schedules.[3] Three DS strategies are commonly implemented:

- **Complete reactive scheduling** has a low computational burden and dispatches resources based on the resource's availability and the priority of tasks in the queue.
- **Robust proactive scheduling** improves the robustness of schedules by studying uncertainties and risk factors within each scheduling item to predicably accommodate disruptive events.
- **Predictive-reactive scheduling** describes an ideal system that establishes a robust initial schedule, adjusts time and resource requirements based on real-time progress updates and revises the schedule logic such as task precedencies and resource capacities dynamically.

The conceptual model of a predictive-reactive dynamic scheduling system is illustrated in Figure 1, comprising three components: ***baseline scheduling***, ***progress update***, and ***rescheduling***. Each of the 3 components evolves with the advent of optimisation and automation technologies to allow predictive-reactive DS systems to generate reliable outcomes.

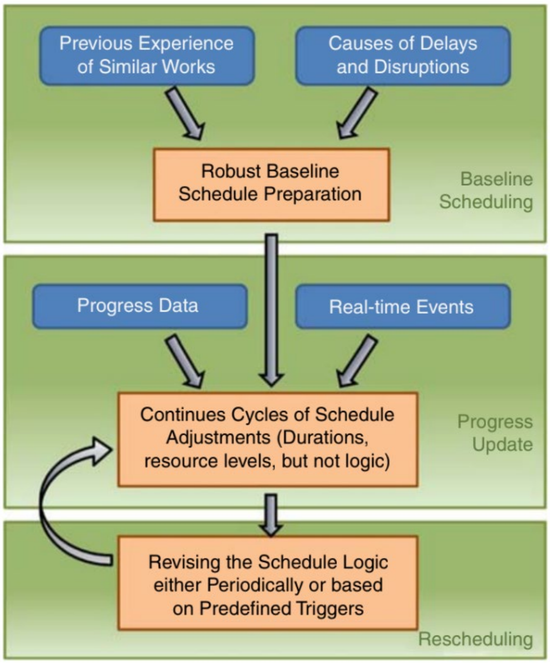


Figure 1. Predictive-reactive dynamic scheduling system.[3]

For example, advanced scheduling methods start to consider the stochastic nature of construction activities, incorporate precedence/resource constraints and employ AI optimisation algorithms to improve robustness. Progress updating, which was manual, tedious, and error-prone, can be automated with emerging tracking and monitoring technologies. Collectively, they could increase the frequency and extent of rescheduling.

The frequency and extent of rescheduling are described as 3 policies and 2 strategies for rescheduling, specifying ***when*** and ***how*** to adjust schedules:[4,5]

- **Rescheduling policies**: (1) periodic rescheduling policy, (2) event-driven rescheduling policy, and (3) hybrid rescheduling policy (a.k.a., rolling time horizon)
- **Rescheduling strategies**: (1) schedule repair and (2) completely reschedule.

Traditionally, the frequency and extent of rescheduling are governed by the type of disruptive events. For example, some disruptive events are at the project level, such as an addition to the original scope and changed project milestones, requiring a complete restructuring of schedules once the events happened; others may be related to resources and operations, such as the insufficient capability of material handling equipment and quality rejections, which are usually identified through regular inspections and addressed locally without disturbing the majority of the plan.

With new methods of scheduling and progress updating, more frequent and optimised adjustments of schedules can be expected. Although DS has not been applied to the construction process systematically, significant productivity gains can be envisioned already: disruptive events are automatically captured and reported to a schedule optimisation algorithm for real-time adjustments, and the scheduling outcomes are continuously improved as data in similar projects accumulates.

4.3 Establishing robust baseline schedules

Some robust scheduling methods for the entire building production process (e.g., PERT) have been introduced in other sections to elevate the robustness of schedules by considering uncertainties and risks. This section further tightens its focus on construction sites and demonstrates several examples of advanced scheduling methods. To emphasise the impacts of productisation, we selected methods designed for prefabricated construction (PC) that either improve the realism of schedules by simulating construction processes or optimise the sequence of construction activities using AI algorithms.

4.3.1 Schedule simulation with constraints, uncertainties and risk factors

A critical task in scheduling is to estimate the duration of construction activities. Traditionally, such estimation is manually crafted based on planners' experience.[6] However, manual estimation methods have a limited computational capacity, and tend to oversimplify the time requirements of construction activities. For example, the duration of construction activities is either determined by one deterministic estimation (as in CPM) or multiple deterministic estimations (e.g., the optimistic, pessimistic and most likely estimations in PERT). In real-world construction projects, however, the durations are more complex as disruptive events, such as severe weather, material quality defects, and delays, constantly occur. As a result, a schedule formulated on manual estimations may be unrealistic.

Researchers have leveraged computer-aided simulations to predict the duration of construction activities and, in turn, the completion time of construction projects.[6] Two techniques are often employed: discrete event simulation (DES) and system dynamics (SD). DES models system operation as a sequence of discrete events in time, which are often used to describe the handling, preparing, and installing activities for PC.[7] Introduced in earlier sections of this report, SD is another widely adopted simulation method that analyses the relationship between complex systems from a holistic view to support project managers' decision making.[8]

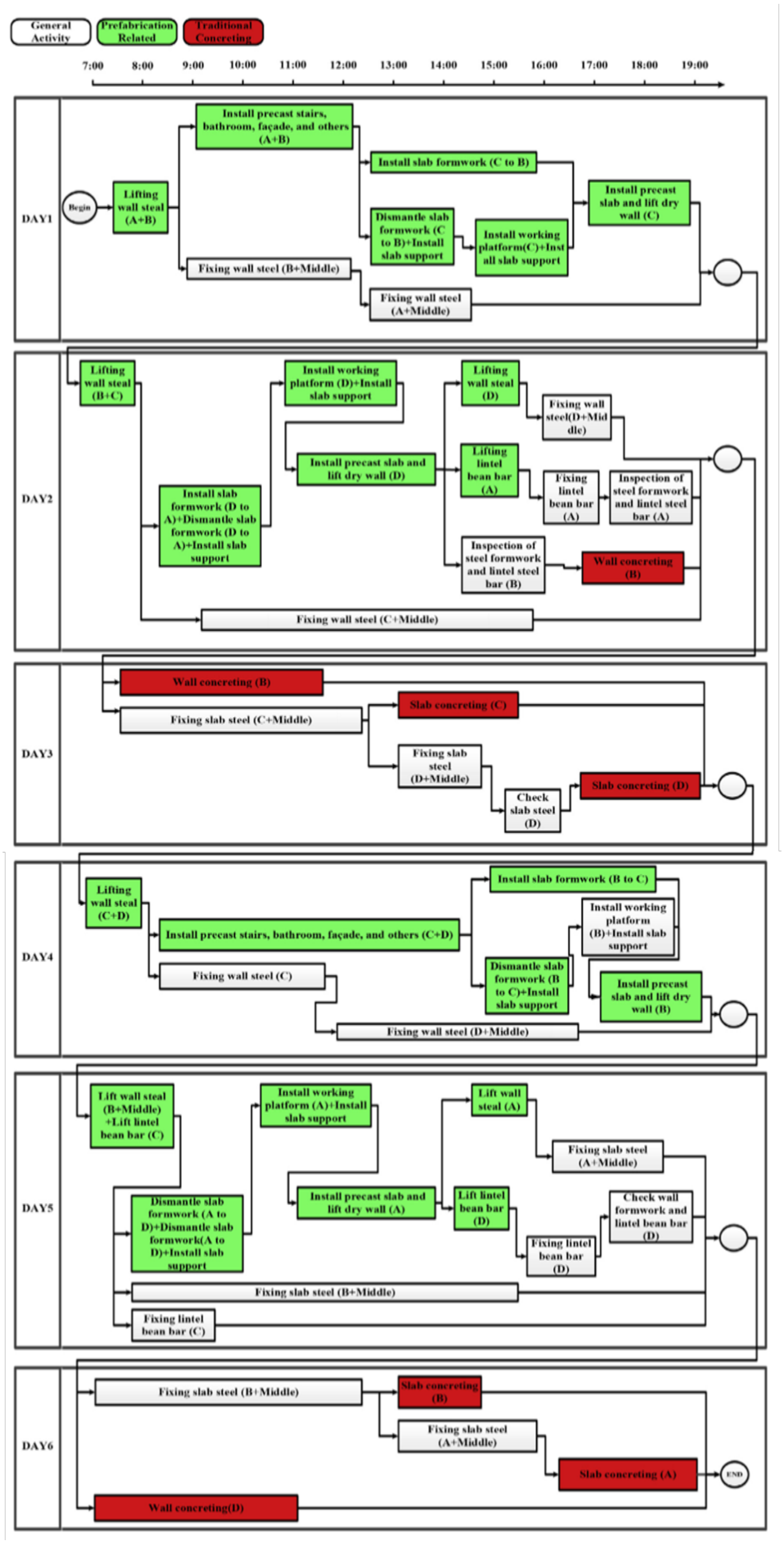


Figure 2. A typical '6-day cycle' of assembly activities.[9]

Combing DES and SD, Xie et al. (2018)[9] proposed a hybrid model to simulate prefabrication housing production (PHP) processes in Hong Kong. DES simulated a 6-day cycle assembly. A 6-day cycle assembly is a critical production unit used in the Hong Kong construction industry to standardise the activity flow of PHP. Figure 2 illustrates the precedence constraints of each activity and colour codes activities into 3 types: general activities (e.g., fixing wall steel), prefabrication-related activities (e.g., lifting and installing precast components), and traditional concreting activities.

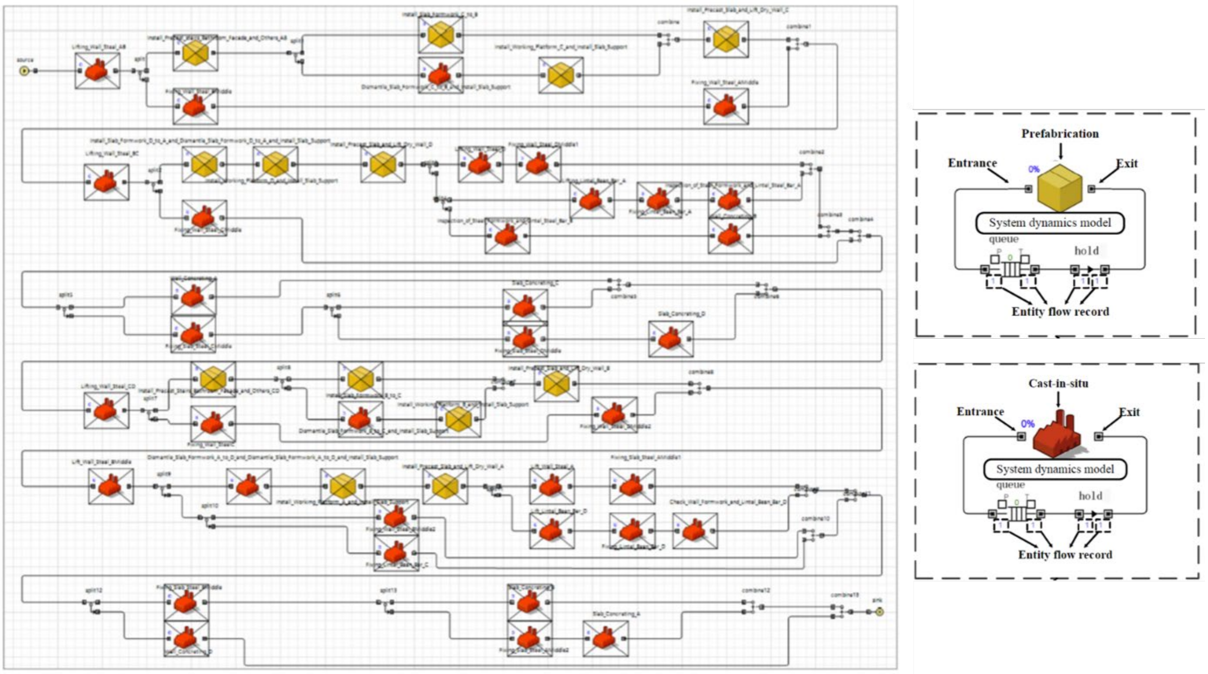


Figure 3. Discrete event simulation (DES) of the '6-day cycle' with each event described with a DS Model.[9]

The precedence constraints (i.e., predecessor and successor relationships) are simulated by a DES model (Figure 3), where each discrete event is depicted by a DS model. As shown in Figure 4, each DS model uses 4 functional modules to describe one construction activity:

1. The prefabrication installation module describes the workflow of lifting, installing, and inspecting activities for a precast building component.
2. The resource allocation module links labour, materials, and machinery-related variables (e.g., the number of workers on-site) and the weather impact on the processing rate of each construction activity.
3. The project quantity calculation module depicts the impacts of design changes by randomly adding delays as construction progresses.
4. The schedule performance module describes the behaviour of the construction site under schedule pressures and links pressure-related variables (e.g., working hours) to the processing rate of each construction activity.

As a result, risk factors in building production processes are parameterised. Project managers can manipulate variables in these 4 modules to estimate the duration of construction activities, which can be used to quantify the effects of some administration decisions (e.g., extending working hours). While this study used DES to simulate precedence constraints only, other DES systems, such as that proposed by Yang et al. (2022)[7] also considered the constraints brought by storage capacities along supply chains. However, few research efforts tested the comprehensiveness of the constraints and risk factors considered in their simulations or validated the simulation results against real-world field data.

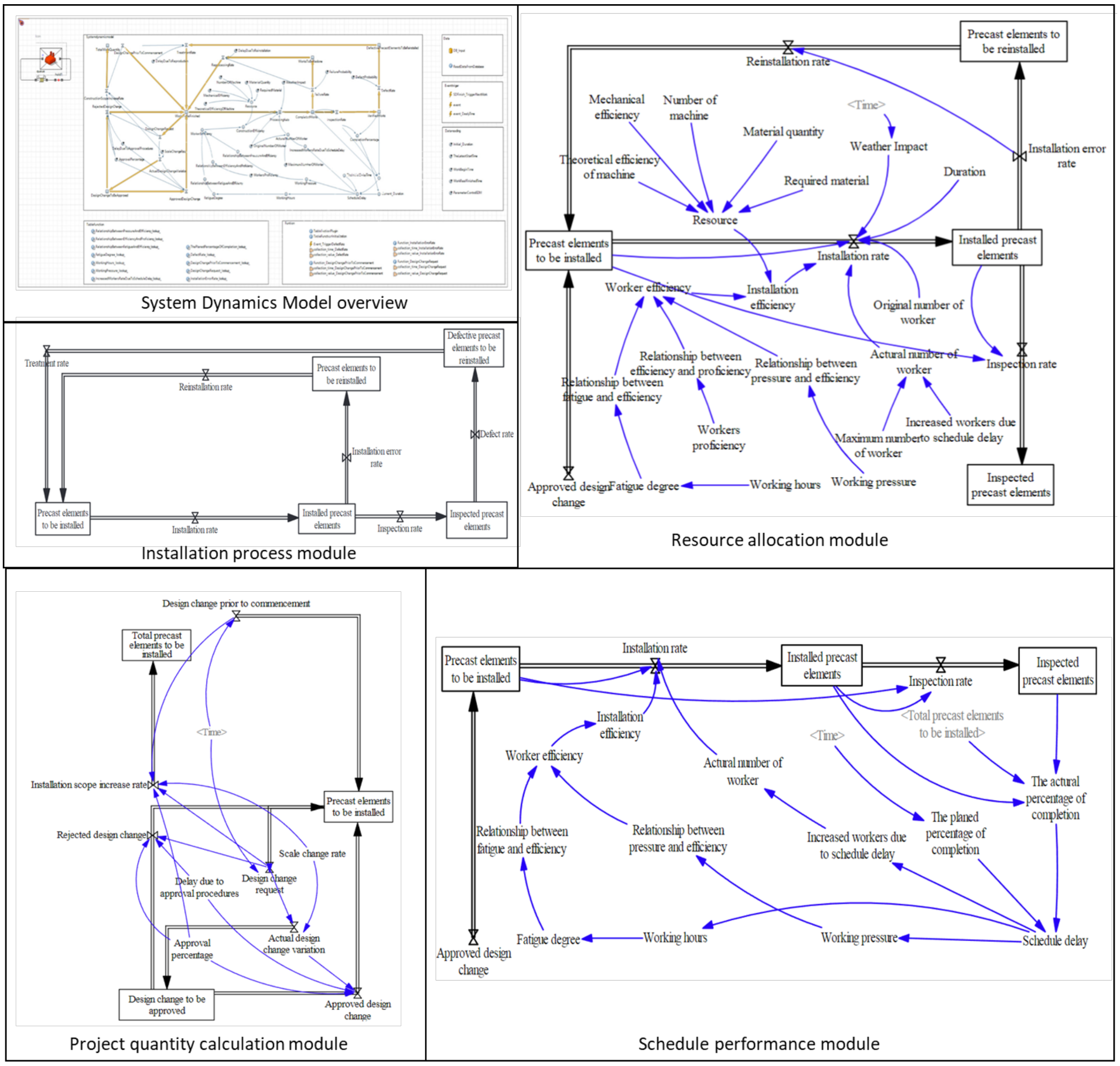


Figure 4. Schematic diagram of the DS Model.[9]

4.3.2 Optimising schedule with AI algorithms

While simulation methods depict risk factors in construction processes, some research assumes construction activities have deterministic durations and resource requirements and attempts to optimise the sequence of these activities with AI algorithms. These studies are similar to CPM in terms of scheduling logic, trying to minimise project completion time considering precedence and resource capacity constraints, but leveraging automated optimisation algorithms to improve efficiency and optimality of scheduling. Two examples are illustrated in Figures 5 [10], 6 and 7.[11]

The Genetic Algorithm (GA) can be leveraged to find the optimal sequence of construction activities (i.e., with the least project completion time) and to generate the Gantt chart and resource histogram automatically.[10] GA is a metaheuristic AI algorithm inspired by natural selection, which uses 4 operators (i.e., initialisation, mutation, crossover, and selection) to explore possible combinations of variables (e.g., sequences of construction activities), evaluate performances of different combinations, and yield a near-optimal outcome.[12] The predecessor–successor relationships and resource requirements of construction activities are listed in Figure 5a, and the automatically generated Gantt chart and resource histogram are presented in Figures 5b and c.

Activity	Activity Number	Predecessor	Duration/Day	*R1*	*R2*	*R3*
Starting	1	-	0	0	0	0
Construction preparation	2	1	1	6	0	0
Plant bolt of A	3	2	1	2	0	6
Column lifting of A	4	3	3	2	24	6
Mounting bracing of A	5	4	1	3	0	4
Grouting of A	6	4	1	2	0	4
Single beam lifting of A	7	5, 6	2	2	24	6
Beam protection of A	8	7	1	2	0	4
Lattice beam lifting of A	9	8	2	3	24	8
Sleeve, bolt connecting of A	10	9	2	3	0	8
Gluing and grouting of A	11	10	1	3	0	6
Plywood hoisting of A	12	11	2	2	24	8
Concrete pouring of A	13	12	1	4	0	4
Plant bolt of B	14	2	1	2	0	6
Column lifting of B	15	14	3	2	24	6
Mounting bracing of B	16	15	1	3	0	4
Grouting of B	17	15	1	2	0	4
Single beam lifting of B	18	16, 17	2	2	24	6
Beam protection of B	19	18	1	2	0	4
Lattice beam lifting of B	20	8, 19	2	3	24	8
Sleeve and bolt connecting of B	21	20	2	3	0	8
Gluing and grouting of B	22	21	1	3	0	6
Plywood hoisting of B	23	11, 22	2	2	24	8
Concrete pouring of B	24	23	1	4	0	4
Ending	25	13, 24	0	0	0	0

R1: managers availability
R2: available lifting equipment (crane and flatbed truck)
R3: labour (crane installation personnel, drilling personnel, and grouting personnel)

a

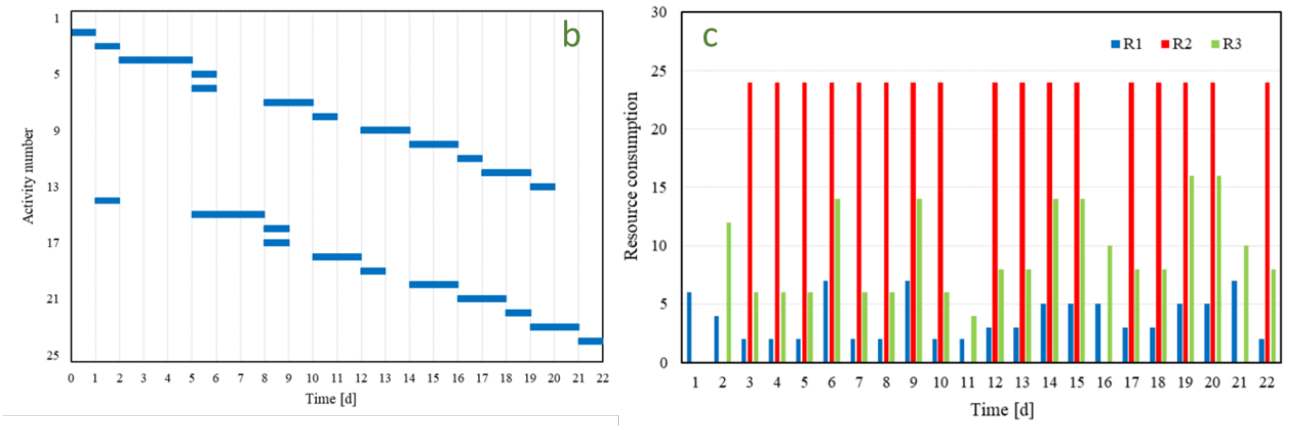
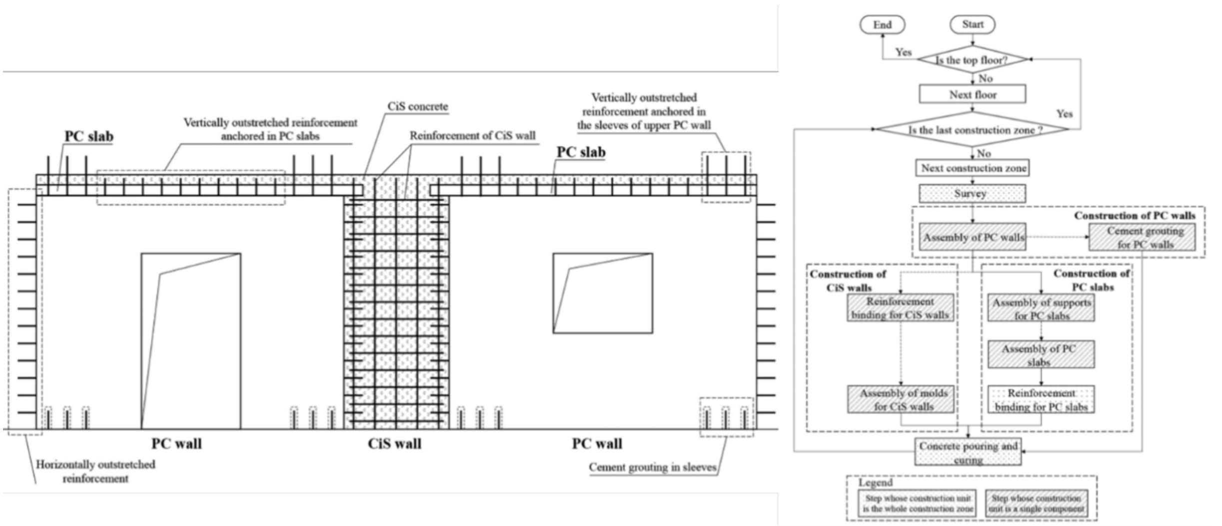


Figure 5. (a) Activities for a prefabricated construction with their precedence constraints and resource demands; (b) the optimal schedule planned by Genetic Algorithm (GA); (c) resource requirements versus construction time.[10]

Similarly, Ma et al. (2021)[11] proposed a schedule optimisation method for hybrid shearing wall structures (cast-in-situ or CiS, and prefabricated construction or PC). Hybrid shearing wall structures are constructed through a unique activity flow (Figure 6), where CiS walls and PC slabs can be constructed concurrently after assembling and grouting PC walls.

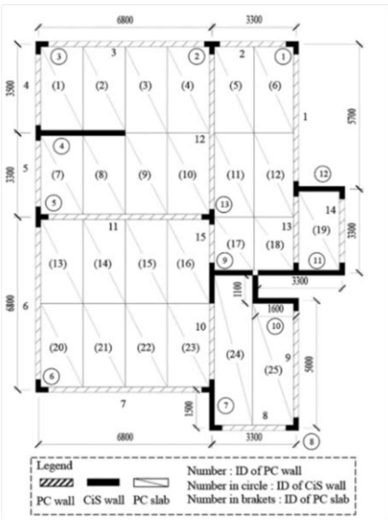


Typical connection of components in a hybrid construction (Cast-in-Situ and Prefabricated Construction or CiS & PC) shearing wall structures

Typical construction process of standard floods in hybrid shearing wall structures

Figure 6. Prior knowledges for a hybrid shearing wall structures (CiS and PC): component connection methods (left) and the activity flow (right).[11]

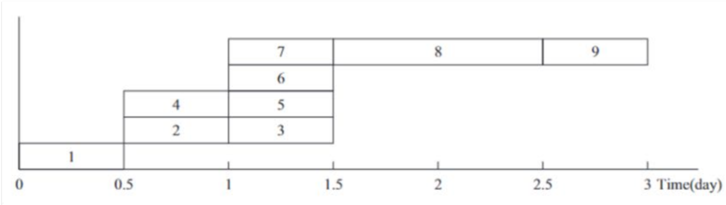
Based on this flow, an AI algorithm called Multi-objective Discrete Symbiotic Organisms Search (MDSOS) was adapted to find the shortest completion time with resource constraints (e.g., availability of crane, specialised workers and general workers). As shown in Figure 7, the proposed method was piloted and compared with manual methods (i.e., benchmark), and the results showed a 16.7% decrease in the project completion time.



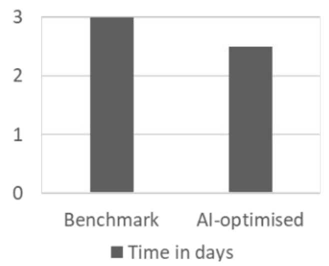
A selected zone for case study

Activity ID (i)	Content	Construction unit	Number of component-level activities
1	Survey	Construction zone	–
2	Assembly of PC walls	Component	15
3	Cement grouting for PC walls	Component	15
4	Reinforcement binding for CiS walls	Component	13
5	Assembly of molds for CiS walls	Component	13
6	Assembly of supports for PC slabs	Component	25
7	Assembly of PC slabs	Component	25
8	Reinforcement binding for PC slabs	Construction zone	–
9	Concrete pouring and curing	Construction zone	–

Activities within the selected zone



Traditional zone-level construction schedule for the selected zone



Comparison of the traditional and AI-enabled scheduling methods

Figure 7. Validating effectiveness of the advanced scheduling method enabled by AI algorithms and component-level precedence and resource-consumption information.[11]

AI algorithms outperform manual scheduling methods in both optimality and efficiency, making them ideal tools to adjust the sequence of construction activities in real time as construction progresses. However, they also share the same sensitivity to prior knowledge with manual scheduling methods. For example, an activity flow has to be predefined and programmed, and resource requirements must be estimated when using these algorithms. Different research works interpret the resource requirements differently, and few interpretations are validated with field data.

4.4 Automating progress updates

With the rapid development of automation in construction, abundant automated progress tracking/monitoring methods have been proposed and piloted on construction sites. Depending on their tracking/monitoring mechanisms, these methods can be categorised into 3 clusters (Figure 8):

1. periodic progress updates
2. process focused real-time event updates
3. disruption focused real-time event updates.

Features of each cluster are elaborated on in the following sections with examples.

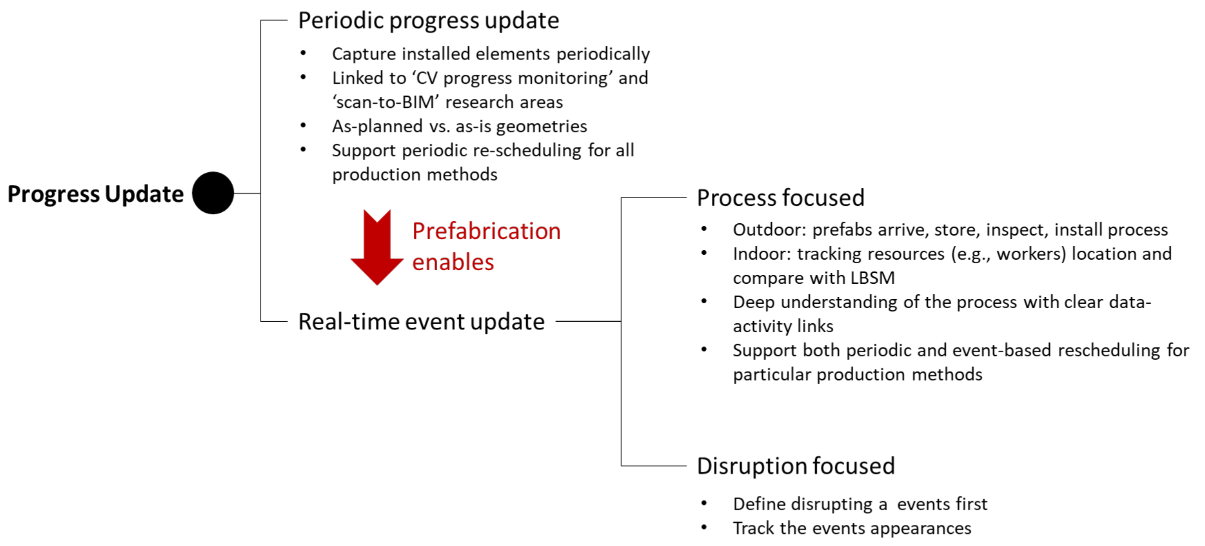


Figure 8. Overview of automated progress update methods.

4.4.1 Periodic progress updates

Conventionally, progress monitoring is performed by site managers who walk around the construction site and observe installed building elements regularly. Site managers rely mainly on visual signals to perceive the construction progress. Thus, it is intuitive to automatically process visual signals computer-vision (CV) [13] and light detecting and ranging (LiDAR) technologies.[14] CV and LiDAR technologies acquire photos and point clouds of the building structure periodically and compare the as-is geometry derived from acquired data with the as-planned geometry from 4D BIM models to detect delays in the construction progress. The key challenge for these automated methods is to extract geometry information from photos or scanned point clouds. Figures 9 and 10 illustrate the mechanisms of geometry extraction for CV [13] and LiDAR-based [14] progress tracking methods, respectively.

As shown in Figure 9, Wei et al. (2022)[13] tracked the positions of the camera and superimposed the positions with photos to interpret the construction progress for interior walls. The interpretation is established on unique surface features of each wall construction activity, such as 'bricklaying', 'plastering', and 'facing brick'. This method relies heavily on the linkage between geometric changes and construction tasks. Therefore, CV-based systems cannot track some activities that cannot result in geometric changes.

Figure 10 presents the mechanism of LiDAR-based progress tracking methods, which is also known as 'scan-to-BIM' or 'scan-vs-BIM' in academic papers.[14] In this example, cross-sections of mechanical, electrical, and plumbing (MEP) components were retrieved from both point clouds and 4D BIM models using an image feature extraction technique (i.e., Hough Transform) and compared with each other to determine the progress of MEP installation activities.

These CV or LiDAR-based progress tracking methods can effectively detect delays of some construction activities (e.g., with predictable and obvious geometric changes), but they cannot explain the causes of schedule deviations. Resources related to construction activities are not tracked; neither are the resource bottlenecks (e.g., the lack of materials, workers, or equipment).

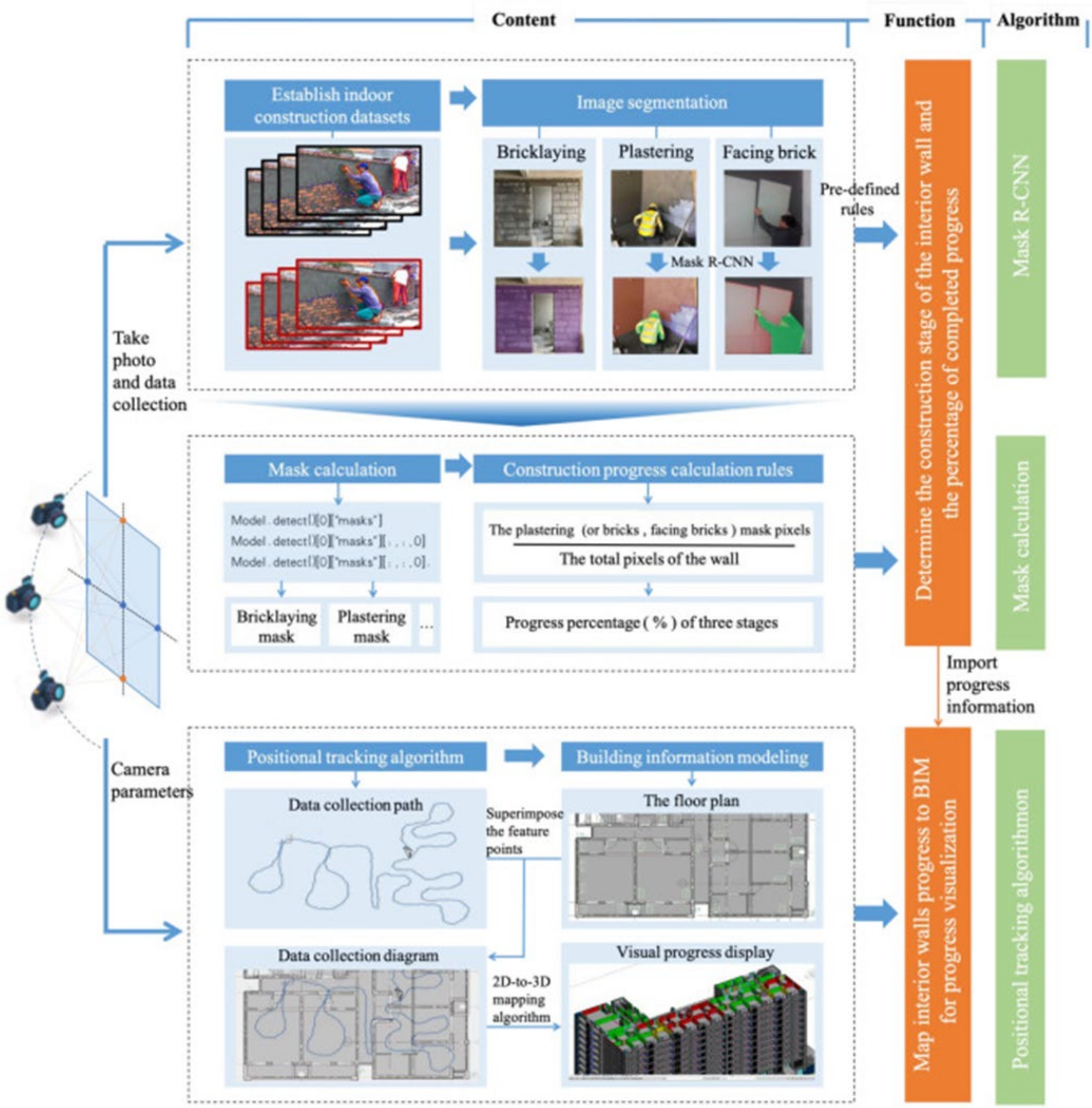


Figure 9. Updating wall construction progress with CV.[13]

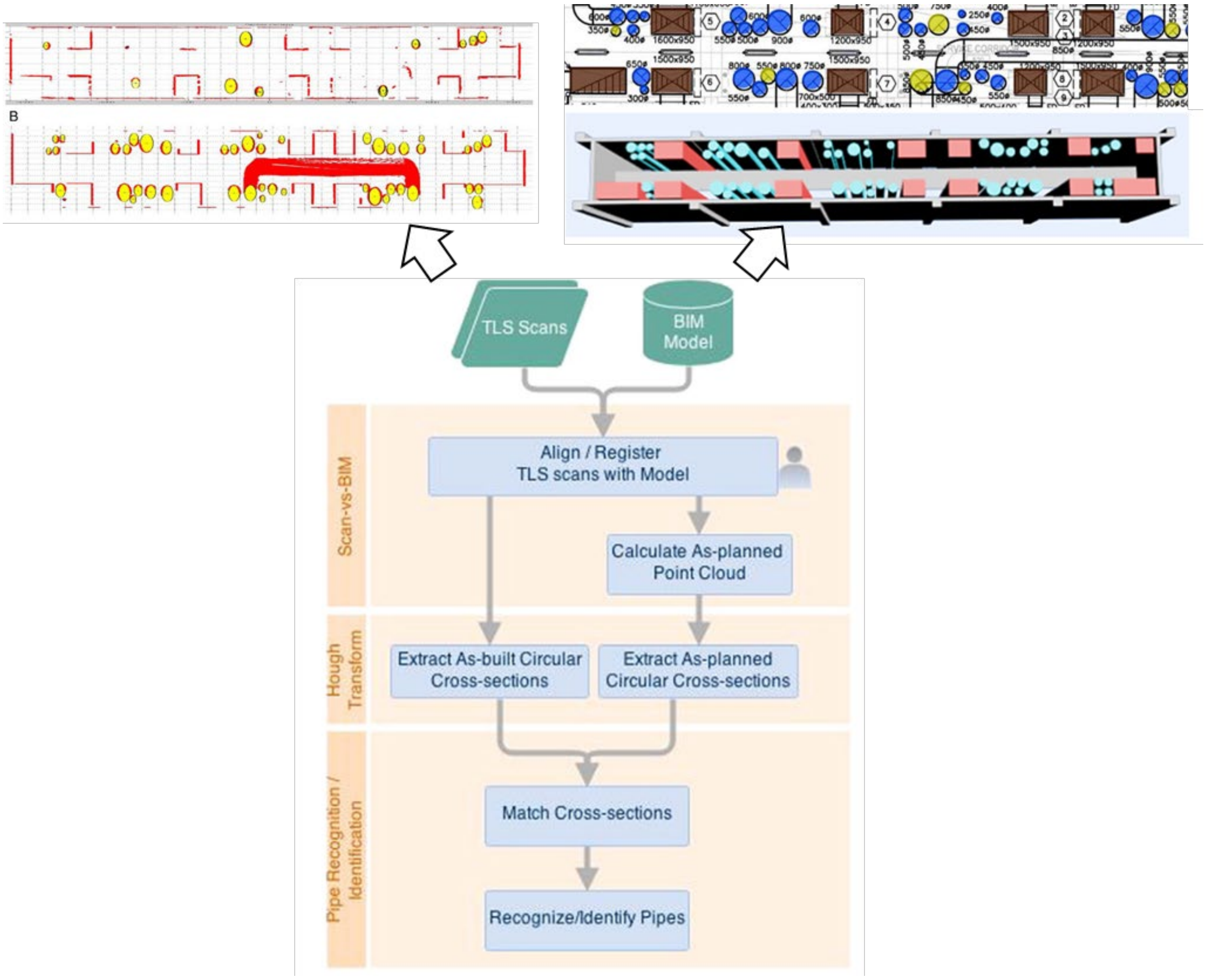
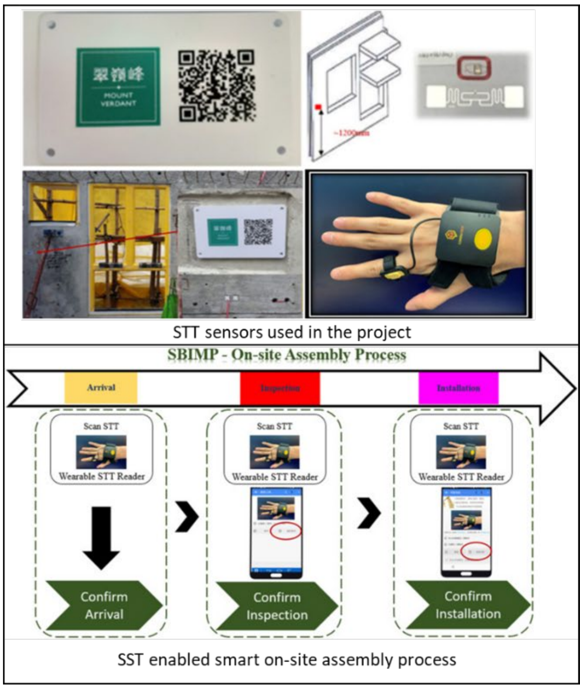


Figure 10. Updating installed MEP components periodically with TLS scans and scan-vs-BIM techniques.[14]

4.4.2 Process focused real-time event updates with resource tracking

Every construction activity consumes or occupies a certain number of resources, such as materials, equipment, and workers. Compared with conventional construction methods, productised construction (e.g., PC) has a clearer activity flow for precast building components (e.g., arrival, storage, lifting, and installation), in which each activity has unique resource requirements (e.g., specialised workers or equipment). These features of productised construction processes provide powerful heuristics for data reasoning. Therefore, automated progress updating methods could track spatiotemporal information of resources to interpret the status of construction activities. We present 2 examples, describing automated progress updating systems for the on-site assembly of precast building components and indoor construction activities, respectively.

Figure 11 illustrates a semi-automated progress tracking system proposed in Zhou et al. (2021).[15] The proposed system uses an STT sensor (i.e., an integrated sensor with a QR code scanner, RFID tag, NFC tag and GPS sensor) to track the arrival, inspection, and installation of precast building components. Synchronising STT signals from different workers (e.g., inspection crew and installation crew) at different locations with building information from BIM models enabled effective communications on site and recorded processing time of different construction activities (e.g., unloading, inspecting, and retrieving building modules). The proposed system was piloted in a government accommodation project in Hong Kong and demonstrated significant enhancements in construction efficiency. For example, the duration of module unloading was shortened by 50% and the number of inspection crew halved.

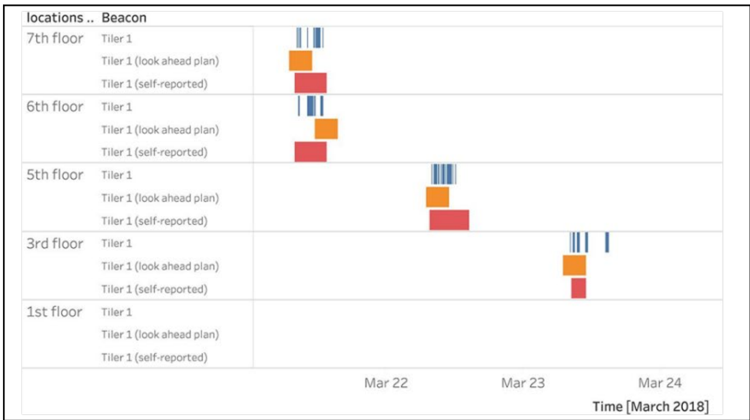


Improvements in KPI items after using SST

KPI items	Description	Before (Average)	After (Average)	Enhancement
Unload time	Average time to unload modules from the truck to the laydown yard	40 min	20 min	50%
Number of inspection crew	Number of crews required for inspecting and unloading received modules	2	1	50%
Information collection time	Average time needed to capture complete time and location information of modules for one zone	5 min	< 1 min	More than 80%
Retrieval time	Time required to retrieve specific modules for installation	2 min	< 1 min	More than 50%
Number of assembly crew	Number of crews required for assembly work	5	4	20%
Error detecting time	Average time to identify the misplaced prefabricated modules	5	< 1 min	More than 80%
Assembly time	Average time to erect modules in the right location for one zone	2.5 h	1.5 h	40%
Emergency detecting time	Average time to notice the urgency regarding the on-site assembly process	10 min	2 min	80%
Feedback time	Average time to make responses and take actions	15 min	2 min	86.70%
Assembly cycle	Time required to complete the assembly and R.C. structure work for one typical floor	5–7 days	4 days	Average 33.3%

Figure 11. Updating the installation process of PC components.[15]

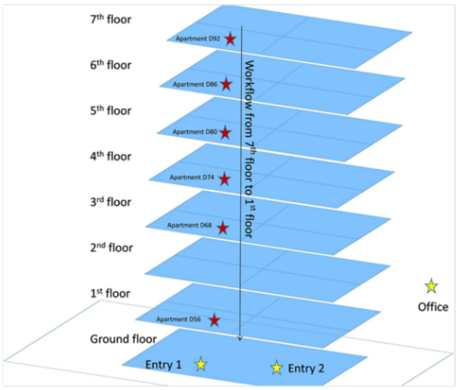
Another example can be found in an indoor activity-focused study,[16] where RFID sensors were installed in different rooms to detect the presence of workers. A resource allocation plan was used to interpret work in progress and establish the relationship between workers' precedence and construction activities (e.g., tiling and painting). As a result, the actual start and end times for each construction activity were automatically captured. Figure 12 shows the sensor deployment plan, location-based resource allocation plan, and the comparison between as-is and as-planned start/end times for different construction activities. The actual start/end time have tangible implications in construction management. This information, as shown in Figure 13, can be used to validate subcontractors' self-reported working hours and to calculate uninterrupted work hours of each trade.



	Task presence indices (PIs)	Presence-to-plan ratios (PPs)	Actual duration/ Planned duration (PPs/PIs)
Masonry of shafts	21%	18%	86%
Preparation of concrete floor pours and pouring	50%	34%	68%
Waterproofing	34%	39%	115%
Tiling	29%	34%	117%
Joints	33%	53%	161%
Suspended ceiling	30%	26%	87%
Caulking of suspended ceiling	43%	33%	77%
Painting of suspended ceiling	32%	10%	31%
Furnishing	23%	11%	48%
Finishing	28%	34%	121%
Shaft drywall	65%	57%	88%
Kitchen furnishing	25%	57%	228%
Average	34.42%	33.83%	98%

Task presence index: $\frac{uninterrupted\ presence\ time\ during\ task}{planned\ duration\ of\ the\ task}$

Figure 12. Use cases of the tracking results: to validate self-reported hours (left) and to determine the uninterrupted work hours (right).[16]



Sensor deployment plan

Tasks (abbreviations)	Work trade	Workers assigned to the task
Masonry of shafts (MS)	Carpentry	Carpenter 1 Carpenter 2
Preparation of concrete floor pours and pouring (PP)	Carpentry	Carpenter 1
Waterproofing (WP)	Tiling	Tiler 1
Tiling	Tiling	Tiler 1
Joints	Tiling	Tiler 2
Suspended ceiling (SC)	Carpentry	Carpenter 1 Carpenter 3
Caulking of suspended ceiling (CSC)	Painting	Painter 1 Painter 2
Painting of suspended ceiling (PSC)	Painting	Painter 1 Painter 2
Furnishing (Fu)	Carpentry	Carpenter 1
Finishing (Fi)	Carpentry	Carpenter 1
Shaft drywall (SD)	Carpentry	Carpenter 2
Kitchen furnishing (KF)	Carpentry	Carpenter 1 Carpenter 4

Location-based resource allocation plan

Tasks	Look-ahead plan		Tracking result	
	Start time	End time	Start time	End time
Masonry of shafts	March 20 7:00	March 20 11:00	March 20 12:42	March 20 15:12
Preparation of concrete floor pours and pouring	March 21 7:00	March 21 11:00	March 21 7:31	March 21 11:04
Waterproofing	March 22 7:00	March 22 11:00	March 22 8:01	March 22 12:05
Tiling	March 23 7:00	March 23 11:00	March 23 8:07	March 23 15:55
Joints	March 27 7:00	March 27 11:00	March 26 9:31	March 27 14:38
Suspended ceiling	April 03 7:00	April 03 11:00	April 03 7:32	April 03 12:13
Caulking of suspended ceiling	April 04 7:00	April 04 11:00	April 04 7:24	April 04 10:09
Painting of suspended ceiling	April 05 7:00	April 05 11:00	April 05 7:29	April 05 9:56
Shaft drywall	March 21 7:00	March 21 11:00	March 21 7:31	March 21 13:11
Kitchen furnishing	March 22 13:30	March 23 8:00	March 22 9:50	March 23 13:06

Comparison of as-planned and as-is activity start/end time

Figure 13. Updating progress of indoor activities with the aid of RFID and location-based resource allocation plans.[16]

4.4.3 Disruption focused real-time event updates

The third cluster focuses on disruptive events. Although this cluster is smaller in terms of the number of research works, it contains some thorough discussions on the relationship between the progress update and re-scheduling, such as in Yan and Zhang (2021).[17] This study used CV technologies to detect objects on the construction site (e.g., trucks, site gates, construction roads, workers, precast slabs) and extract the spatiotemporal relationships among them, such as the timestamps when trucks pass the site gate and the duration of trucks on construction roads.

A limited number of disruptive events were defined, including material arrival delay, jobsite traffic block, PC installation delay, and ergonomic posture-related work delay. Descriptions and the objects to be detected for each event are listed in Figure 14. With these predefined objects and object relationships, photos from site cameras can be translated to the duration of disruptive events, which were used for rescheduling as described in the next section. Figure 15 illustrates the 4 disruptive events with photos from a live construction site. Although effective in detecting these events, this study did not discuss whether these 4 disruptive events can completely cover all types of disruptions on a PC site. In fact, it is extremely difficult to enumerate disruptive events and explicitly define the objects to be detected for them.

No.	Disruption	Description	Objects to be detected
1	Material arrival delay	Arrival of mixer truck loaded concrete or truck loaded PCs at construction site is behind schedule.	Mixer truck and PC-loaded truck.
2	Jobsite traffic block	Construction trucks or labors at work block the path of a moving construction truck.	Mixer truck and PC-loaded truck.
3	PC installation delay	The installation of PCs on building structure is behind the schedule.	Prefabricated slab and prefabricated wall.
4	Ergonomic posture–related work delay	The schedule of ergonomic posture–related works is delayed due to lack of workerpower, ergonomic hazards, or low productivity.	Worker's posture.

Figure 14. Defining the disruptions.[17]

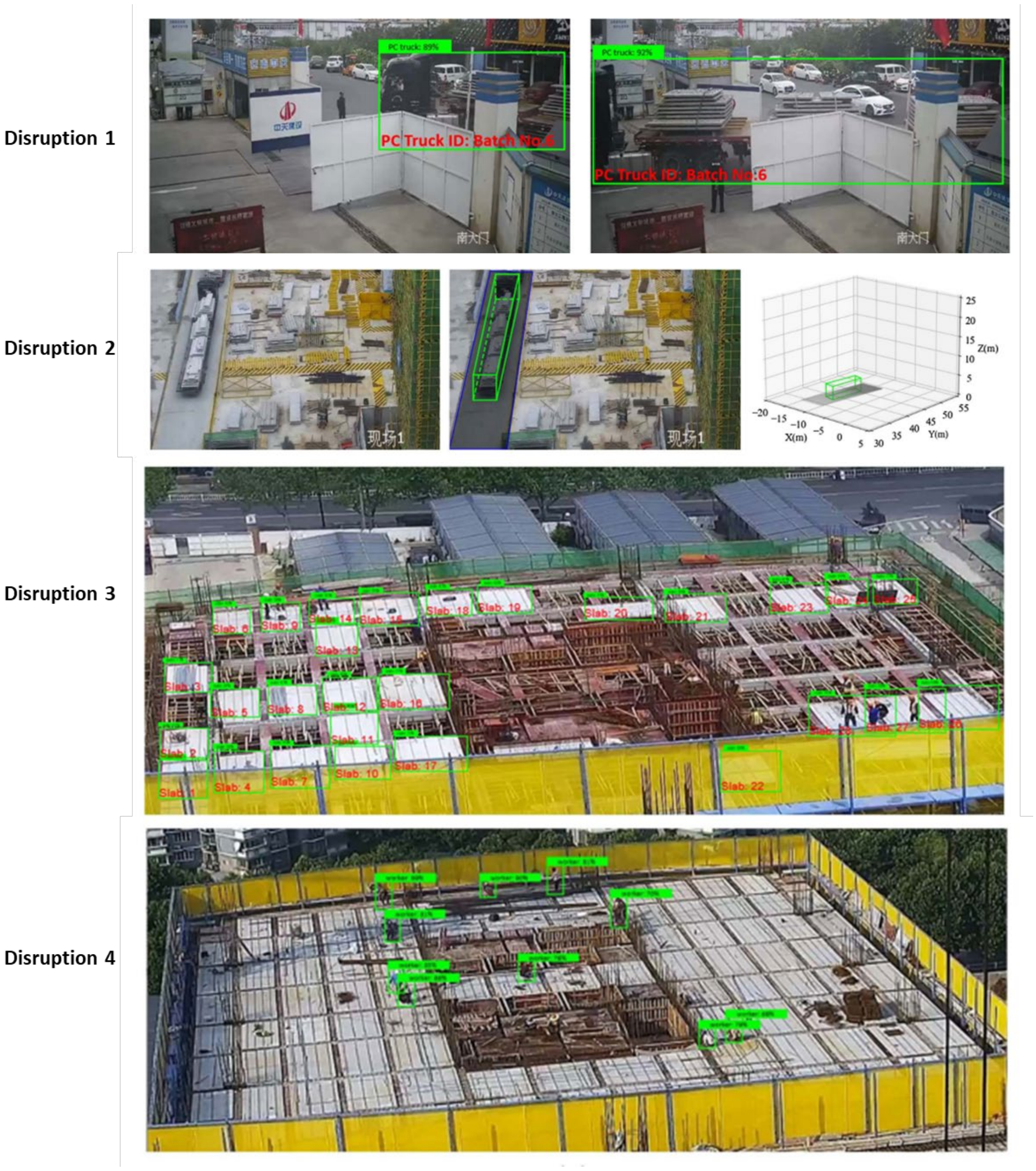


Figure 15. Detect disruptive events with CV methods.[17]

4.5 Rescheduling

4.5.1 Automated schedule repair

With disruptive events detected, Yan and Zhang (2021)[17] further proposed a schedule repairing algorithm to minimise negative impacts on the construction progress. As shown in Figure 16, the schedule repairing algorithm has 2 steps: (1) evaluating the scope of disruptions by calculating the delayed time; and (2) running an AI optimisation algorithm to minimise the deviation of remaining activities from pre-determined schedules. From a DS perspective, this algorithm enables the schedule repair strategy (introduced earlier) to be implemented automatically. However, it is only applicable to minor delays of activity durations, reflecting **an underlying assumption for this schedule repairing algorithm: activities' precedence is not changed by disruptive events.** Errors may be generated when significant changes in scheduling logic happen.

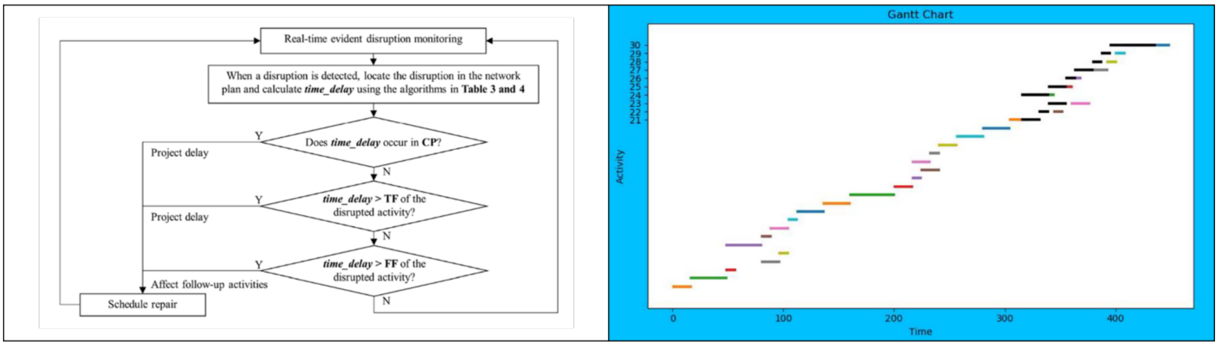


Figure 16. Schematic representation of an automated schedule repair method (left), where black lines means the adjusted durations of activities (right).[17]

4.5.2 Real-time resource-driven scheduling

While schedule repairing algorithms adjust durations of construction activities reactively, some researchers investigated proactive coordination of on-site resources to minimise delays. A recent publication from Hong Kong proposed a digital twin-enabled method to automatically allocate appropriate resources spatiotemporally for modular integrated construction (MiC).[18] The study argued that PC with a sufficient level of assembly (LoA), such as MiC, usually has a standardised activity flow and resource requirements (as shown at the top of Figure 17), so that on-site activities are predictable in a near future. Based on the real-time status of on-site resources, a schedule for the near future can be generated in real-time (as shown at the bottom of Figure 17) with delays anticipated before construction activities commence. Three critical resources were coordinated in this study: on-site storage areas, crane availability, and installation crew availability. Although unrealistic assumptions were made to neglect quality rejections, the idea of 'detecting the spatiotemporal information of resources to enable proactive coordination' sheds a light on future construction digital twin studies.

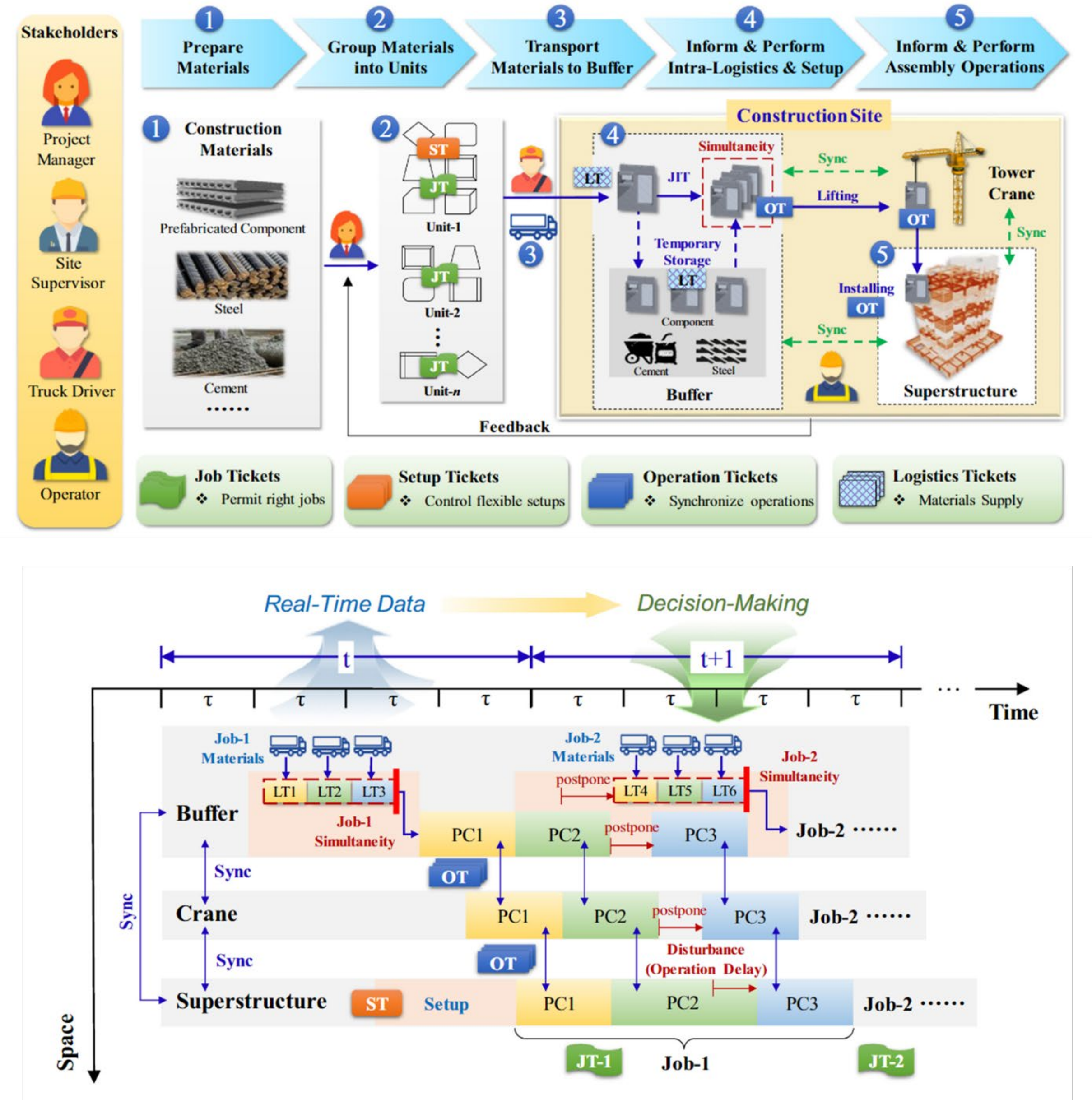


Figure 17. Process map of Modular integration Construction, MiC (top) and automated resource (crane, workers and storage spaces) allocation based on the detected installation progress of individual modules (bottom).[18]

4.6 Conclusions and future research opportunities

The concept of dynamic scheduling (DS) is usually discussed in the manufacturing industry, where the production process has been standardised, monitored, and automatically controlled. In recent years, researchers and the construction industry have extensively explored the application of ICT technologies on the construction site, bringing enhanced situation awareness of on-site resources (e.g., locations and status of equipment, workers, and materials). Meanwhile, PC shifted a large number of on-site activities away to plants, making the construction process more controllable. As a result, a great capacity is expected for adjusting building production processes dynamically and maximising resource utilisation and efficiency.

This chapter reported the state-of-the-art in construction scheduling, progress monitoring/tracking, and schedule adjustments, which demonstrated the maturity of point solutions in each domain. However, their level of fragmentation hinders the implementation of DS for on-site activities. Particularly, feedbacks from progress monitoring/tracking results to scheduling are lacking. First, the resource requirements used to arrange construction activities are usually guesstimated, while the actual data of resource consumption is not retrieved when adjusting the schedules. Second, there is an information gap between scheduling methods and progress tracking methods. Many tracking systems rely on heuristics (e.g., resource allocation plans), but such heuristics are missing in some predefined schedules. For example, locations (zones) are important information for reasoning sensor-capture data, while many construction projects do not employ location-based scheduling (LBS) or takt planning.

Thus, there is demand for mapping as-planned and as-is data at the activity level. A standardised data structure should be created or tailored based on existing data structures as a specification of conceptualisation for on-site activities so that as-planned data and as-is data of the same entity (e.g., durations, crane usage, or workers) can be retrieved from different information sources. Figure 19 illustrates an ontological model of schedule, describing a construction activity with 6 elements: (1) action, (2) object, (3) location, (4) resource, (5) condition, and (6) actor.[19] Data could be extracted from databases (e.g., MS projects and datasheets of sensors) or even paper-based documents, drawings, and site images with the aid of natural language processing (NLP) and CV technologies. Curating data scattered in different information systems or paperwork like this will enable the accumulation of knowledge within an organisation and deliver values by identifying disparities between as-is and as-planned data or improving the duration/resource estimation for construction activities.

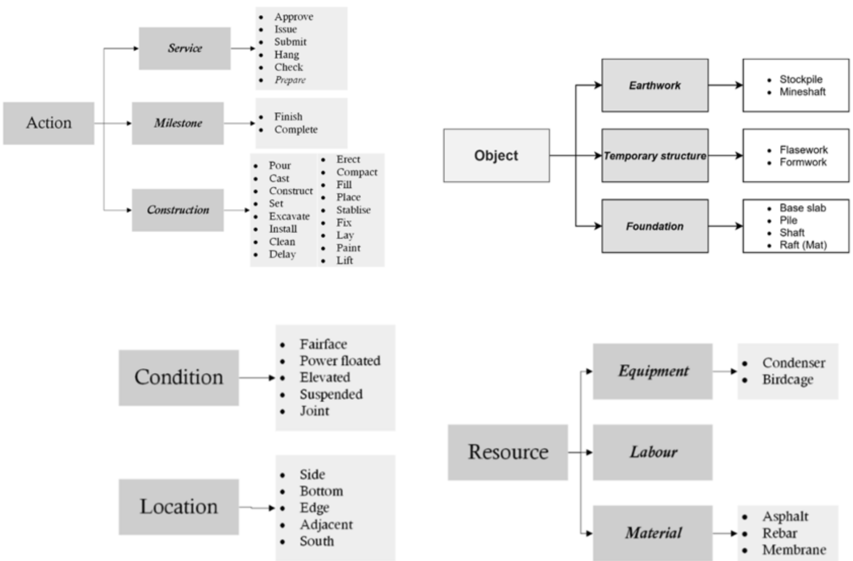


Figure 18. Elements for a construction activity in schedules.[19]

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CHAPTER 5 CONTENTS

CHAPTER 5: MARKET REVIEW: DYNAMIC SCHEDULING SOFTWARE

Nicolas Diban, Dr. Felix Hui

5.1 Executive summary

This chapter provides an overview of the construction project management and scheduling software market, focusing on software that enhances productised construction. It covers the features and capabilities of these software solutions and the market research process to compare and evaluate different options.

After analysing 96 software solutions that included project management and construction management software, as well as other related solutions, 7 software with productisation capabilities, 16 project management software programs, an Application Platform as a Service (aPaaS) for construction, and a scheduling enhancer solution were shortlisted based on the exclusion criteria. Among construction software solutions with productisation capabilities, Dassault Systemes has received the highest rating in modularity, interoperability, functionality and customisation. In the project management software category, Autodesk has been awarded the highest ratings in the same categories. Other software solutions have also been highly rated in their respective categories.

Finally, the chapter highlights the key factors to consider when selecting a project management information system and presents a shortlist of software solutions for construction project management and scheduling.

5.2 Introduction

Project management information systems provide an elevated perspective of activities and progress in a centralised platform that incorporates scheduling and tracking capabilities necessary for the success of a construction project. These software solutions comprise a wide variety of products, including work management tools, portfolio management solutions, scheduling, analytics, and project management software.

Conducting market research becomes necessary to compare and evaluate the different solutions using similar parameters, because there are hundreds of vendors to choose from. As a reference, compare and review websites such as Capterra list 171 results when searching for ‘construction scheduling software’.

Modular, productised, or offsite construction adds additional complexities to the scheduling process because more variables must be considered. Consequently, a software solution that enhances a productised construction lifecycle must account for its distinct characteristics.

This chapter presents a comprehensive overview of today’s construction project management and scheduling software in the market, considering the particularities of a productised approach.

5.3 Research method

The present market research was carried out using a literature review approach. This encompassed exploring pertinent terminologies via the Google search engine, perusing review websites such as Capterra and project-management.com, and inspecting social media sources, particularly LinkedIn groups focusing on construction scheduling and productisation. We generated a comprehensive list of potential solutions, and then analysed vendor websites to incorporate supplementary information about primary features, targeted client company size, interoperability, and scheduling capabilities to define a definitive list of software solutions.

5.3.1 Criteria for inclusion and exclusion

Software solutions were not shortlisted if:

- the primary focus was on work management or organisational workflows
- the focus was on construction workflows or document management without strong scheduling capabilities
- the company is not present or does not offer support in Australia
- their target segment is small or medium enterprises and projects.

5.3.2 Key definitions used

Interoperability

This research defines interoperability as the capacity to connect or integrate with other project management software. For example, some applications can import and export different file types, some offer direct synchronisation, and some have application programming interfaces (APIs) that facilitate data sharing.

Each software solution's interoperability capacity was classified into 5 levels:

- Level zero depicts no software interoperability.
- Level one considers the capacity to import other file types.
- Level two interoperability suggests the capacity to import and export other file types.
- Level three indicates the presence of APIs that allow interoperability.
- Level four suggests the presence of open APIs that facilitate interoperability.

Level of customisation

We used 4 levels of software customisation to categorise the software studied in this market research, based on the description by Sun et al. (2008).

- Level zero relates to highly standardised software with no configuration.
- Level one customisation entails predefined parameters configuration, including corporate design, customised reports, custom user-defined tabs, forms, fields, and buttons. In some cases, it allows the creation of different roles with different dashboards.
- Level two customisation allows users to tailor the solution to their organisation's particularities using plug-ins, APIs, and encapsulated user functions to extend or enhance the packaged software's built-in capabilities.
- Level three customisation involves source code changes and new custom software module additions to packaged software customised to the organisation's requirements.

5.4 Overall results

We generated a list of 96 software solutions, which included project management suites, construction management software, and work management software with scheduling capabilities, among other related complementary solutions. The aforementioned software solutions are detailed in Appendix 1. After applying the exclusion criteria, we shortlisted 7 software solutions with productisation capabilities, 16 project management software programs, an Application Platform as a Service (aPaaS) for construction, and a scheduling enhancer solution.

The software packages are presented in alphabetical order and grouped by category.

5.4.1 Construction software with productisation capabilities

1. CadMakers – cmExe
2. Dassault Systemes Delmia
3. Donovan Group – AirBuildr
4. Offsight
5. SiteDrive
6. Trunk Works Ltd.

7. Vizz technologies – Manufacton

5.4.2 Project management software

1. Autodesk Construction Cloud
2. Bentley Systems – SYNCHRO & ProjectWise
3. Deltek OpenPlan and Acumen
4. Doxel Schedule
5. Elecosoft Powerproject
6. Exigo – Vico Office, Vico Control
7. InEight
8. Microsoft Project
9. Oracle Primavera P6
10. PMA Technologies: NetPoint and Schedule MD
11. Procore Technologies, Inc.
12. Schüco – PlanToBuild
13. StratusVue – PlansandSpecs
14. Trimble Connected Construction
15. Veyor
16. Visilean

5.4.3 Complementary software

1. Kahua
2. SmartPM Technologies

5.5 Construction software with productisation capabilities

5.5.1 CadMakers

CadMakers cmExe is a production tracking and optimisation software platform. It integrates the supply chain, fabrication, logistics, and installation in a single web-based hub. It is complemented by cmBuilder, a 4D site logistics simulation software, and cmKnowledge for knowledge capturing and collaboration.

Price	Platforms	Based in	Year founded
Custom quote	Cloud, SaaS, Web-based	British Columbia, Canada	2014

Interoperability: cmBuilder.io + Procore integration. Dassault Systemes integration.

Level of customisation: Customised forms, fields and templates. Fully customisable production processes and workflow. Customisable user roles and permissions.

Cases, projects or clients: 600+ projects; 45 key projects.

Website: https://www.cadmakers.com/cmcore

5.5.2 Dassault Systemes

Dassault Systemes Delmia Construction, Cities & Territories solution supports construction simulation, real-time tracking capabilities, lean construction methodologies, modular construction, smart logistics, and value-stream mapping. In addition, Dassault Systemes offers software for 3D product design, simulation, manufacturing, and other 3D-related products, including its software CATIA and 3DEXPERIENCE for virtual twin technology.

Pros: Claims to have off-site construction capabilities and optimisation, including reduced modular construction time by 70%.

Price	Platforms	Based in	Year founded
Custom quote	Cloud, SaaS, Web-based	Vélizy-Villacoublay, France	1981

Modularity integration: CadMakers.

Interoperability: API-based, no details specified. Third-party providers offer integration with most tools.

Level of customisation: Robust API, Java, Widgets/Webservices, Enterprise knowledge language, Eclipse.

Cases, projects or clients: 84 customer stories. A global ecosystem of over 1,500 clients.

Website: https://www.3ds.com/products-services/delmia/solutions/construction-cities-territories/

5.5.3 Donovan Group

Donovan Group's AirBuildr is a construction design software package that dynamically generates engineering for portalised buildings. AirBuildr sets a workflow while automating a commercial construction project's modelling, loading, optimisation, design, and calculation engineering stages. The company claims the design process is at least 20 times faster than standard engineering methods when using their software. It is complemented by uTecture, an integrated architectural design platform.

Price	Platforms	Based in	Year founded
Custom quote	Cloud, SaaS, Web-based	Whangarei, New Zealand	2012

Interoperability: Any other analysis systems with an open API can interface with AirBuildr.

Level of customisation: No explicit information on their website besides mentioning the use of APIs.

Cases, projects or clients: No clients showcased.

Website: https://donovangroup.com/airbuildr/

5.5.4 Offsight

Offsight is a manufacturing project management software for the off-site construction and building components industry. The software streamlines collaboration between project managers, quality inspectors, production supervisors, and other stakeholders to keep factory projects on track.

Pros: Partnered with building component associations, organisations and providers across the world.

Price	Platforms	Based in	Year founded
Custom quote	Web/Cloud	California, USA	2020

Interoperability: Autodesk Construction Cloud PlanGrid.

Level of customisation: Customised dashboard.

Cases, projects or clients: 24 customer success stories.

Website: https://www.offsight.com/

5.5.5 SiteDrive

SiteDrive is a scheduling and project management software. It focuses on strong visual scheduling capabilities, dynamic communication, development collaboration, and tracking. SiteDrive claims to have digitalisation, modularisation, and takt production capabilities.

Price	Platforms	Based in	Year founded
Custom quote	Cloud, SaaS, Web-based, App	Espoo, Finland	2002

Interoperability: Not specified.

Level of customisation: Customised dashboard.

Cases, projects or clients: SiteDrive is used by over 2,000 professionals in Nordic countries. The website showcases 6 clients.

Website: https://sitedrive.com/

5.5.6 Trunk Works

Trunk is a software platform for off-site manufacturing and site assembly giving real-time visibility of programs for manufacturers, clients, and project stakeholders.

Pros: Trunk incorporates a dynamic scheduling AI that helps reduce waste and increase manufacturing throughput.

Price	Platforms	Based in	Year founded
Custom quote	Web/Cloud	Manchester, UK	2021

Interoperability: Integrates with other software MS Office, MS Dynamics 365, Oracle Netsuite, Sage, and Autodesk.

Level of customisation: No information.

Cases, projects or clients: 3 cases, 3 clients (IBM, TREK, and Patchwork), and 1 magazine appearance.

Website: https://trunk.works/

5.5.7 Vizz technologies

Vizz technologies Manufacton is a dynamic scheduling system (cloud-based software) that helps manage end-to-end off-site construction processes. It facilitates the standardisation of factory processes to leverage BIM models to generate bills of material, produce kits and assemblies, simplify collaboration, track materials and inventory, and coordinate deliveries to the job site.

Pros: Presents 3 cases.

Price	Platforms	Based in…	Year founded
Custom quote	Web/Cloud	Georgia, USA	2014

Interoperability: Integrates with other software MS Project, Primavera, Procore, SysQue, Viewpoint, Acumatica, evolveMEP, and Autodesk.

Level of customisation: Basic configuration.

Cases, projects or clients: Presents 4 cases. Claims that it was used for 2,500+ buildings and produced more than 175,000 prefabs.

Website: https://www.vizztechnologies.com/modular-builder

5.6 Project management software

The following section outlines project management software that can be utilised for construction scheduling and, in some instances, supplemented with other software solutions for modular capabilities or off-site construction requirements. Although Microsoft Project and Oracle Primavera were not designed exclusively for construction, they were included due to their wide-ranging application and compatibility with modular-specific software. Wherever possible, user reviews were retrieved from Capterra.com.au.

5.6.1 Autodesk

The Autodesk Construction Cloud includes solutions for office and field teams considering the design, planning, construction, and operations phases to help make construction more predictable, safe, and sustainable. Autodesk provides a set of BIM and CAD tools supported by a cloud-based common data environment that facilitates project delivery from early-stage design to construction.

The Autodesk system is built on a unified platform that includes Autodesk Build (Connect field and project management workflows), Autodesk BIM Collaborate Pro (Cloud-based design collaboration software) and Autodesk TakeOff (Generate accurate estimates produced from integrated take-offs and quantities). These tools allow the creation of high-quality, high-performing building and infrastructure designs with conceptual and detailed design tools. Further, it facilitates optimising projects with integrated analysis, generative design, visualisation, and simulation tools. Lastly, it includes analytics to improve predictability in the field with tools that maximise constructability and project coordination.

Pros: Autodesk includes Navisworks, Revit, and Assemble, allowing the integration of BIM data from design to construction.

Price	Platforms	Based in	Year founded
Starting price: USD 49.00/month	Cloud, SaaS, Web-based, Windows (Desktop), Android and IOS (Mobile)	California, USA	1982

Number of reviews	Overall rating	Ease of use	Customer support	Features	Value for money
1,885	4.3	4.1	4.2	4.1	4.0

Modularity integration: Offsight, Trunk and Vizz technologies Manufacton.

Interoperability: Oracle Primavera, MS Excel, MS Project, Autodesk Navisworks, On Center, Intelliwave, Sage, Buildingconnected, Procore, PlanGrid, Fieldwire, Aconex, Ineight planswift, SYNCHRO, CMIC, Newforma, and Offsight. Trimble Interoperability Agreement (API). Assemble can be dynamically connected with Primavera P6.

Level of customisation: Autodesk FBX SDK and API. Forge apps for the Autodesk app store. Customised dashboards provide different roles, users or companies with relevant dashboards. Allows creating private dashboards.

Cases, projects or clients: Multiple customer stories in multiple locations on every continent.

Website: https://www.autodesk.com/collections/architecture-engineering-construction/overview

5.6.2 Bentley Systems

Bentley Systems SYNCHRO is a project management suite with 4D scheduling and task management capabilities. It is complemented by SYNCHRO Scheduler, a software that provides project planning and scheduling software with an advanced CPM engine. Additionally, ProjectWise 365 provides seamless project collaboration in the cloud and ProjectWise facilitates on-demand analytics and trends.

Price	Platforms	Based in	Year founded
- SYNCHRO Large WorkSuite USD 37,500 - Medium WorkSuite USD 19,550 - Small WorkSuite USD 7,920	Cloud, SaaS, Web-based, Windows (Desktop), Windows (On-Premise), Linux (On-Premise), Android and IOS (Mobile)	Pennsylvania, USA	1984

Number of reviews	Overall rating	Ease of use	Customer support	Features	Value for money
29	4.7	4.3	4.5	4.3	4.2

Interoperability: Interoperable with all major BIM and scheduling formats. Import, export, and synchronise to and from Oracle Primavera, Microsoft Project, Microsoft Excel, PMA Netpoint, and Asta Powerproject.

Level of customisation: Basic configuration, including form customisation. Bentley Systems includes SYNCHRO Link, a server and Integration API that connects to SYNCHRO Workgroup Project. Also, Bentley provides SDKs.

Cases, projects or clients: 12 featured big projects.

Website: https://www.bentley.com/en/products/product-line/project-delivery-software

5.6.3 Deltek

Deltek Open Plan is a multi-project analysis, critical path planning, resource management, and risk analysis software. Deltek also supplies Acumen, a project analysis and schedule optimisation software solution.

Price	Platforms	Based in	Year founded
Custom quote	Cloud, SaaS, Web-based, Windows (Desktop), Windows (On-Premise), Linux (On-Premise), Android and IOS (Mobile)	Virginia, USA	1983

Interoperability: Unspecified. Claims to sync with popular out-of-the-box third-party solutions, publicly accessible API stacks and robust data integration and sharing.

Level of customisation: Deltek API SOAP/XML, REST/XML, and REST/JSON. Basic configuration and customised reporting capabilities.

Cases, projects or clients: 43 customer stories. Claims to be trusted by 30,000 organisations around the world.

Website: https://www.deltek.com/

5.6.4 Doxel

Doxel Schedule is a real-time construction optimisation platform. By contextualising vast amounts of disparate project data across the site, BIM, schedule, and budget, Doxel empowers teams with an objective view of their project today and an accurate prediction of where it will be tomorrow. Doxel features AI-Powered Project Controls. It is marketed as a just-in-time software for lean construction with BIM functions software included.

Price	Platforms	Based in	Year founded
Custom quote	Cloud, SaaS, Web-based	California, USA	2017

Interoperability: Import files from Smartsheet, MS Project, Primavera, Powerproject, and SYNCHRO.

Level of customisation: Basic configuration.

Cases, projects or clients: One case study and 4 big clients advertised.

Website: https://www.doxel.ai/doxel-schedule

5.6.5 Elecosoft

Elecosoft Powerproject is a project planning, management and risk analysis software. The suite includes Powerproject Enterprise, which allows multiple users to work collaboratively across project files and Powerproject Vision which enables users to view live project data across all projects by seamlessly connecting all projects and programs in one central location. Elecosoft also markets IconSystem, a cloud-based collaborative BIM software and Site Progress Mobile that enables site staff to update project progress at any time from any location, regardless of an internet or mobile connection and synchronises with Powerproject.

Pros: Available in stand-alone, enterprise and cloud versions.

Price	Platforms	Based in	Year founded
USD 1,575/one-time	Cloud, SaaS, Web-based, Windows (Desktop)	London, UK	1986

Number of reviews	Overall rating	Ease of use	Customer support	Features	Value for money
31	4.5	4.3	4.6	4.6	4.4

Interoperability: Works directly with files from Microsoft Project and Oracle Primavera within Powerproject. Seamlessly integrates with estimating applications such as Bidcon, Enterprise Resource Planning (ERP) systems and BIM tools. Compatible with Elecosoft Easyplan.

Level of customisation: Not specified. IconSystem includes an inbuilt API.

Cases, projects or clients: Used by 100,000 professionals worldwide. Multiple big clients are listed on their website.

Website: https://elecosoft.com/products/powerproject/

5.6.6 Exigo

Exigo Vico is a comprehensive solution that includes 4D scheduling and resource management. In addition, the software includes a cost planner, document controller, location breakdown structure manager, production controller, schedule planner, takeoff manager, work package manager, and web services.

Price	Platforms	Based in	Year founded
Custom quote	- Windows (Desktop) - Vico Office Web Services (VOWS)	Aarhus, Denmark	2010

Note: Some sections of the website were not translated into English.

Interoperability: Import directly from ArchiCAD, Tekla, Revit, and AutoCAD. REST interface.

Level of customisation: Modular software design allows users to purchase different functions or packages.

Cases, projects or clients: 14 clients showcased.

Website: https://vicooffice.dk/en/

5.6.7 InEight, Inc.

InEight is an integrated construction management software. InEight includes support for every project phase, including: scheduling capabilities and features to manage risk and design; estimate and project cost management; safety, quality and commissioning; field execution management; connected analytics; collaborative document management; capital and contract management; and virtual design and construction.

Price	Platforms	Based in	Year founded
Custom quote	Cloud, SaaS, Web-based, Mac (Desktop), Windows (Desktop), Windows (On-Premise), Linux (On-Premise), Android and IOS (Mobile)	Arizona, USA	1989

Number of reviews	Overall rating	Ease of use	Customer support	Features	Value for money
14	4.4	3.8	3.8	4.4	4.1

Interoperability: UNIFIER: Trimble Viewpoint + InEight Estimate integration. Primavera, MS Project, MS Excel, Deltek Open Plan and Autodesk. API.

Level of customisation: InEight API and plug-ins. Customised forms, documents, and dashboards.

Cases, projects or clients: 27 client cases. USD 1 trillion+ worth of construction projects.

Website: https://ineight.com/

5.6.8 Microsoft Corporation

Microsoft Project is a project management tool for planning and scheduling. It was considered because it is extensively used and, therefore, integrable with most construction software and their own Microsoft Office and Teams.

Price	Platforms	Based in	Year founded
Project Plan 5 AUD 75.50 user/month Project Professional 2021 AUD 2,099	Cloud, SaaS, Web-based, Windows (Desktop), Windows (On-Premise), Linux (On-Premise)	Washington, USA	1975

Number of reviews	Overall rating	Ease of use	Customer support	Features	Value for money
1,365	4.4	4.0	4.4	4.4	4.0

Modularity integration: Trunk and Vizz technologies Manufacton integration.

Interoperability: Mainly with other Microsoft programs. JavaScript APIs.

Level of customisation: JavaScript APIs. Customisable dashboard, layouts, fields and functions.

Cases, projects or clients: 35 successful customer stories (showcased on their website). Multiple proven successful cases.

Website: https://www.microsoft.com/en-au/microsoft-365/project/project-management-software

5.6.9 Oracle

Oracle Primavera Cloud is a project control and scheduling software for construction projects. Oracle Primavera P6 Enterprise Project helps plan, prioritise, manage, and execute projects, programs, and portfolios. Moreover, Oracle Construction Intelligence Cloud Service provides AI and analytics solutions suites, Aconex for project collaboration and document management, Textura Payment Management for payment flows, and Oracle Preconstruction for bid management. Primavera was considered because it is extensively used and integrable with other construction software, just like Microsoft Project.

Pros: Multiple proven successful cases and supports lean construction.

Price	Platforms	Based in	Year founded
Custom quote	Cloud, SaaS, Web-based, Windows (Desktop), Windows (On-Premise), Linux (On-Premise)	Texas, USA	1977

Number of reviews	Overall rating	Ease of use	Customer support	Features	Value for money
155	4.4	3.7	3.9	4.3	4.0

Modularity integration: Trunk and Vizz technologies Manufacton integration.

Interoperability: MS Project (XER, XLS, XLSX, or CSV files).

Level of customisation: Java-based API. Customisable dashboard and layouts.

Cases, projects or clients: 25 construction and engineering cloud customer stories featuring big clients.

Website: https://www.oracle.com/au/industries/construction-engineering/primavera-cloud-project-management/

5.6.10 PMA Technologies

PMA Technologies NetPoint is a dynamic and responsive project planning tool. Instead of using the critical path method (CPM), PMA Technologies developed the Graphical Path Method™ (GPM®), which shows the logical relationships of dated objects – such as activities, subtasks, milestones, and benchmarks – in a time-scaled network diagram with high visual impact. PMA Technologies also markets Schedule MD™, a software used to analyse metrics and determine schedule reliability, and NetRisk,™ to accurately predict project completion dates and costs.

Pros: Dynamic critical path analysis, multiple calendars option, custom non-work days, and weather modelling.

Price	Platforms	Based in	Year founded
- USD 3,000/one-time (cloud) - USD 1,950/per-user (Licence)	Cloud, SaaS, Web-based, Windows (Desktop), Windows (On-Premise), Linux (On-Premise)	Michigan, USA	2008

Number of reviews	Overall rating	Ease of use	Customer support	Features	Value for money
26	4.6	4.5	4.6	4.5	4.4

Interoperability: NetPoint in the Cloud supports import/export with Primavera P6 v. 6-8, Microsoft Project 2007 and later, and Microsoft Excel 2010 and later. NetPoint schedules can be imported from and exported to Primavera P6, Deltek Open Plan, and Microsoft Project while only exported to Synchro Professional. Activities and resources can also be defined in Excel and imported into NetPoint, while NetPoint can export reports to Excel.

Level of customisation: Basic configuration.

Cases, projects or clients: 6 case studies.

Website: https://pmatechnologies.com/netpoint/

5.6.11 Procore Technologies, Inc.

Procore Technologies Project Management incorporates construction management capabilities from tendering to the closeout phase. Procore also supplies Workforce Planning, a software for resource management that helps contractors with labour scheduling, forecasting, communications, certification tracking, and labour analysis. Likewise, it features preconstruction and financial management solutions. Procore's platform is powered by the Procore App Marketplace, an open app marketplace that fosters third-party development, 300+ integrations, apps, and services.

Pros: The plan includes unlimited users, unrivalled support, unlimited data storage, and product enhancements at no additional cost

Price	Platforms	Based in	Year founded
- Starting Price USD 375/month - Custom quote	Cloud, SaaS, Web-based, Android and IOS (Mobile)	California, USA	2001

Number of reviews	Overall rating	Ease of use	Customer support	Features	Value for money
2,492	4.5	4.4	4.6	4.3	4.1

Modularity integration: CadMakers and Vizz technologies Manufacton integration.

Interoperability: Asta Powerproject, Grit Virtual, LCM Digital, LeadTime, Microsoft Project, Microsoft Project Desktop Sync, Microsoft Project Online Sync, NextPort, Oracle Primavera, PointFuse, ProjectControls.online, ProperGate, SlatPlanner, Smartsheet Sync, Touchplan, among others.

Level of customisation: Custom and configurable fields (Field name and type). Customised reports. Procore's Custom Solutions team specialises in building customised forms and workflows as an add-on service for the Procore web application. In addition, the App market and API make it possible for a company to build an APP for their own use.

Cases, projects or clients: 1,000,000+ projects in 150+ countries. 59 case studies. 12,000+ companies.

Website: https://www.procore.com/en-au

5.6.12 Schüco

Schüco PlanToBuild is a comprehensive software for construction project management. It includes functions for scheduling, task management, construction reports, defect management and reporting, and multi-project management.

Pros: Data security and process reliability: SSL encryption, redundant data storage, cloud storage on German servers, GDPR-compliant data protection, and customised access rights.

Price	Platforms	Based in	Year founded
- Per user/external users/Data storage - 100 Euro/month (as the base rate with the starter pack)	Cloud, SaaS, Web-based, Android and IOS (Mobile)	North Rhine-Westphalia, Germany	2019

Interoperability: Not specified.

Level of customisation: Basic configuration.

Cases, projects or clients: 7 success stories showcased.

Website: https://plantobuild.online/en/

5.6.13 StratusVue

StratusVue PlansandSpecs is an integrated platform to manage projects from design to operations. It includes project manager, cost manager, document manager, bid manager, and BIM capabilities.

Price	Platforms	Based in	Year founded
Custom quote	Cloud, SaaS, Web-based, Android and IOS (Mobile)	Illinois, USA	2001

Number of reviews	Overall rating	Ease of use	Customer support	Features	Value for money
2	4.5	5.0	4.5	5.0	5.0

Interoperability: Not specified.

Level of customisation: Allows basic configuration. The software is designed in modules, so customers can purchase the ones they need.

Cases, projects or clients: 26,423+ projects are being built worldwide using StratusVue. 80+ featured clients.

Website: https://stratusvue.com/#projectmanagement

5.6.14 Trimble Inc.

Trimble Connected Construction includes different software to manage the plan, design and engineering, program and project management, fabricate and construct, and operate and manage stages. The suite contains ViewpointOne, a construction management suite for job costing, project management, service management, employee management, and data and reporting. Also, Viewpoint Spectrum, a component of Trimble Construction One, is an all-in-one web-based construction ERP. Trimble ProjectSight is marketed as the project management software for designers and contractors which connects to Construction One, Viewpoint ERP, and a mobile app for on-site productivity. Trimble Tilos scheduling and planning software provides a simplified, visual look at the construction project through a powerful linear scheduling view. In addition, Tilos allows running project simulations by connecting the schedule and a project map, including schedule analysis and visualisation.

Pros: Multiple software for different industries with multiple success cases. ViewpointOne construction management suite is proclaimed as a solution for modular projects.

Price	Platforms	Based in	Year founded
Tilos – USD 4,290.00/one-time	Cloud, SaaS, Web-based, Mac (Desktop), Windows (Desktop), Windows (On-Premise), Linux (On-Premise), Android and IOS (Mobile)	California, USA	1978

Number of reviews	Overall rating	Ease of use	Customer support	Features	Value for money
208	4	3.9	3.9	3.9	3.6

Interoperability: Autodesk Interoperability Agreement (API). InEight Estimate integration.

Level of customisation: Trimble APIs and SDKs. Custom user-defined tabs, forms, fields, and buttons.

Cases, projects or clients: 49 customer stories. A million monthly active users of Trimble Connect.

Website: https://construction.trimble.com/en/

5.6.15 Veyor Digital

Veyor Digital is a cloud-based scheduling and planning software designed to optimise on-site operations in the construction industry.

Price	Platforms	Based in	Year founded
Custom quote	Cloud, SaaS, Web-based, Android and IOS (Mobile)	NSW, Australia	2017

Interoperability: AppVeyor REST API.

Level of customisation: AppVeyor REST API. Processes, procedures, forms, and user privileges can be tailored.

Cases, projects or clients: 8 case studies. 14+ big clients showcased.

Website: https://www.veyordigital.com/

5.6.17 VisiLean

VisiLean is a collaborative planning workflow featuring dynamic planning and reporting, integrating lean and BIM. The platform includes human resources, administrative, procurement, design, safety, inventory, quality, design, and information management capabilities.

Note: Present in many countries but does not have offices in Australia.

Price	Platforms	Based in	Year founded
Custom quote	Cloud, SaaS, Web-based, Android and IOS (Mobile)	London, UK	2015

Number of reviews	Overall rating	Ease of use	Customer support	Features	Value for money
43	4.3	4.3	4.8	4.1	4.3

Interoperability: Primavera, MS Project, MS Excel, and ASTA Powerproject (Now Elecosoft).

Level of customisation: Customised layout.

Cases, projects or clients: 14 featured clients.

Website: https://visilean.com/

5.7 Complementary software

5.7.1 Kahua

Kahua is an open, collaborative construction program and project management low-code platform. It includes a marketplace containing more than 600 apps.

Price	Platforms	Based in	Year founded
Custom quote	Cloud, SaaS, Web-based, Android and IOS (Mobile)	Georgia, USA	2009

Interoperability: Open API allows for fully customisable integrations. Existing integration includes MS Project, Primavera, Autodesk, and Trimble Viewpoint.

Website: https://www.kahua.com/

5.7.2 SmartPM Technologies

SmartPM is a construction scheduling analytics software and project controls platform. SmartPM's Schedule Intelligence™ Technology transforms construction schedule data into actionable insights and analytics understood at all levels.

Price	Platforms	Based in	Year founded
USD 280 or 400 per month/project	Web/Cloud	Georgia, USA	2016

Interoperability: Integrates with Procore. Can import files from Oracle and MS Project.

Website: https://smartpmtech.com/

5.8 Software comparison

Leading software solutions in the industry offer specialised products with unique benefits that cater to specific organisation requirements. Therefore, conducting a thorough comparative analysis of the key features is recommended to ensure selection of an optimal construction project management solution.

Figure 1 compares the short-listed software solutions based on the previously defined customisation and interoperability levels.

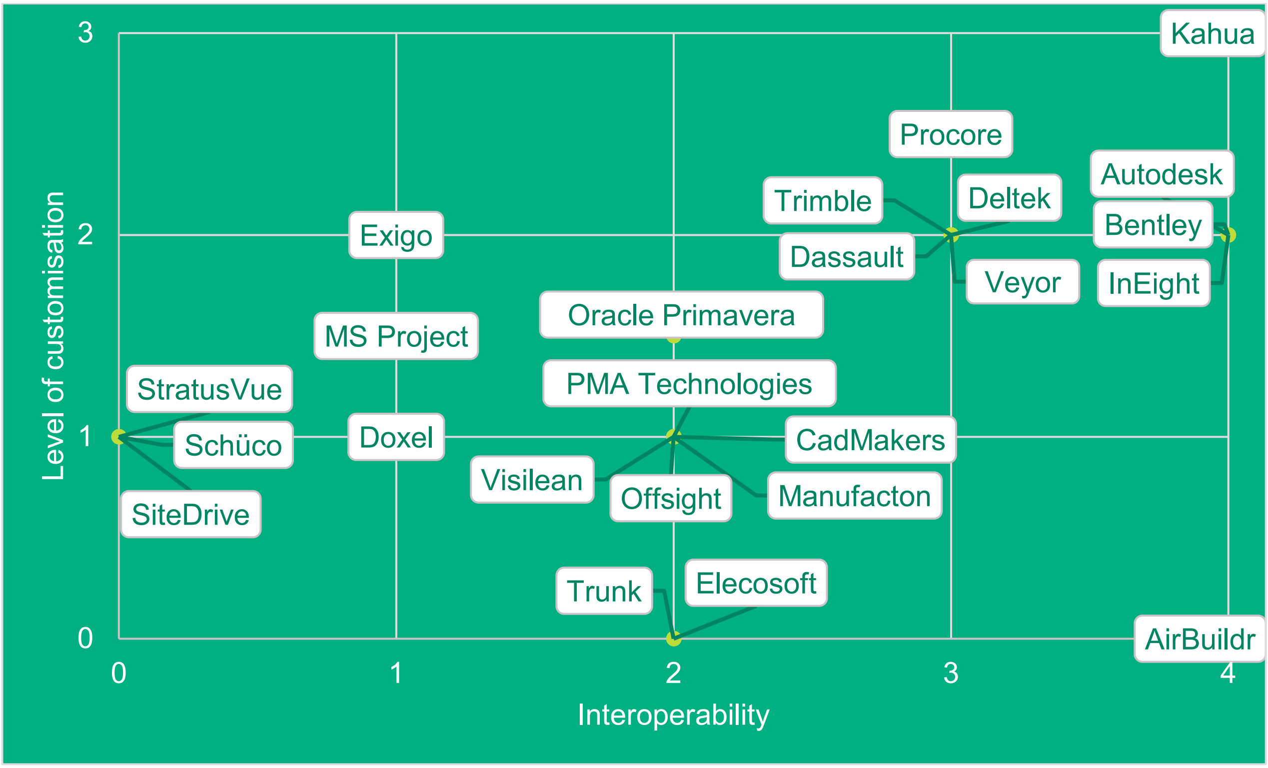


Figure 1. Comparison of software suites interoperability and customisation capacities.

Figure 2 compares the different software packages' overall functionality and modularity capabilities. Functionality describes the number of features the software contained, including BIM, document management, bidding, design, ERP, resource management, etc. Products that offered one key project management feature were rated ‘0’, while products that help to manage the complete project lifecycle were rated ‘5’.

Modularity relates to modular or off-site features or integration with offsite software. Products that offered a no modularity solution were rated ‘0’, while products that either integrated off-site capabilities or were interoperable with off-site software were rated ‘3’.

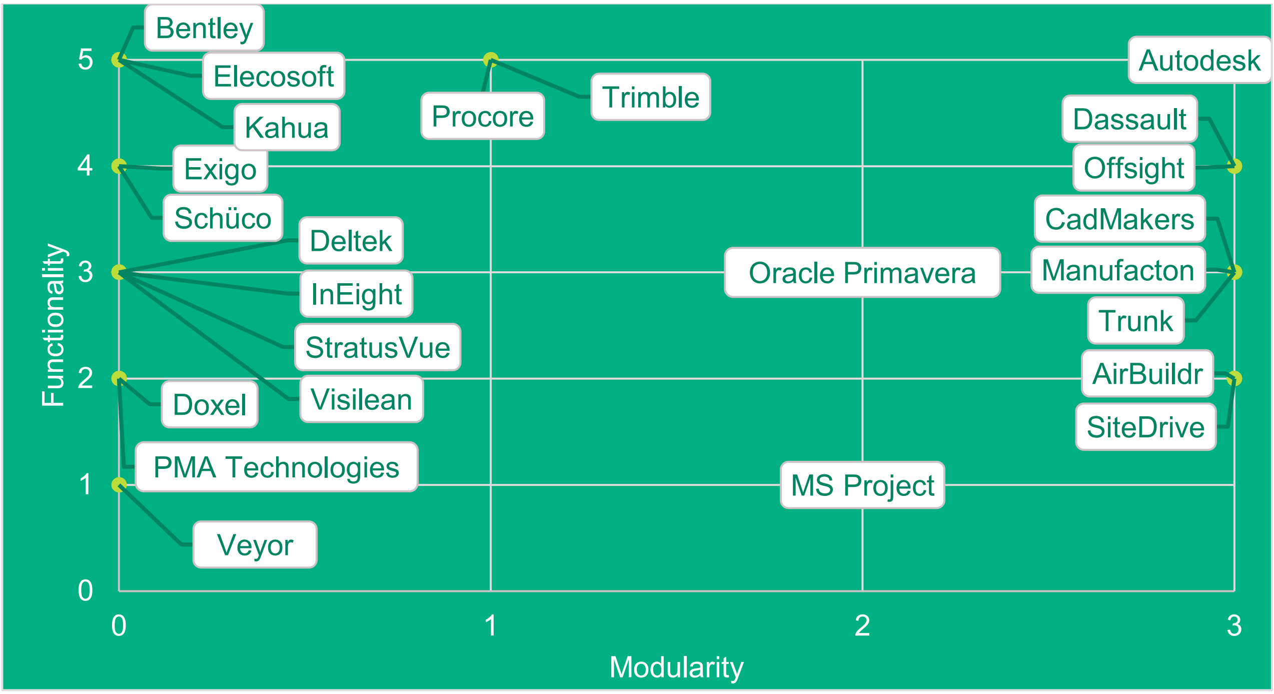


Figure 2. Comparison of software suites’ modularity capacity and overall functionality.

5.9 Recommendations

We recommend organisations thoroughly evaluate the features, pricing, and compatibility with existing systems before deciding on a software solution. Additionally, it may be beneficial to consult with industry experts or seek a software recommendation from a construction technology consultant.

Based on current market research, Dassault Systemes receives the highest rating for functionality and modularity among the construction software solutions with specific productisation capabilities. Dassault offers API-based interoperability, and third-party providers offer integration with a diverse range of tools. The level of customisation is robust, because it includes the use of APIs.

In the Project Management Software category, Autodesk receives the highest rating for functionality and modularity. Moreover, it offers extensive customisability through its APIs and is compatible with most software and file formats.

While Dassault Systemes and Autodesk received the highest ratings, it is important to acknowledge other software solutions that have also received high ratings in these areas within their respective categories, as displayed in Figures 1 and 2.

Lastly, Kahua should be noted as a comprehensive platform that offers the highest level of customisability, although the client is responsible for developing the modularity functions.

5.10 Limitations encountered in the market research process

The process used to evaluate software solutions is subject to limitations. First is the inconsistent and ever-changing nature of the data, which may be biased or overstated because most of it is obtained from vendor websites. These sites focus on selling their products and often highlight features without providing evidence or context, such as claiming to be 20 times faster without explaining how or what they are comparing. Additionally, some websites make broad statements about aspects like interoperability and file format support, but the information is not easily comparable due to inconsistencies across different sites.

Second is the variation in the number and date of user reviews for different software solutions. This disparity can lead to assessment biases, because products reviewed by a large number of users may receive different scores than those reviewed by a small number. Further, some reviews may be outdated, as software companies constantly add new features and updates. As a result, comments and reviews considered for comparison may have been written for different versions of the software or years apart.

Third is some software vendors offer incentives for users to submit reviews, which may influence the honesty and objectivity of the feedback. Thus, not all reviews may result from the user's initiative. So, it is crucial to consider these limitations and gather information from various sources to ensure an unbiased and comprehensive evaluation of software solutions.

5.11 Conclusion

The primary objective of this study was to present an overview of the main features and productisation capabilities of project management software products available in the market. Further, the selection process should consider the organisation’s particularities and project lifecycle since different software include different capabilities, interoperability, and customisation levels.

Additional factors that can enhance the decision making process when selecting a project management information system encompass the following:

- whether all or most of the required features are included
- alignment of the software’s performance with the organisation’s necessities
- expected duration of implementation
- previous experiences with the vendor/software
- ease of use and navigation
- vendor support and responsiveness
- compatibility with the organisation’s supply chain partners.

Importantly, project teams can test and evaluate the software in the early stages of the project, because most vendors offer the option to request a demo. Moreover, we recommend as many end-users as possible test the software solutions considered. This can minimise biases or overstatements induced by the vendor’s claims on their website and test the compatibility between the organisation and the software solution.

Further, we recommend numerous end-users test the software solutions under consideration. This can minimise biases or overstatements induced by the vendor's claims on their websites and test the compatibility between the organisation and the software solution.

5.12 References

Sun, W., Zhang, X., Guo, C. J., Sun, P., & Su, H. (2008). *Software as a Service: Configuration and Customization Perspectives.* 18–25. https://doi.org/10.1109/SERVICES-2.2008.29

Appendices

Appendix 1: Long list of software solutions for project scheduling

Construction software with productisation capabilities

Company	Software name	Description	Web	Comments
CadMakers	cmExe	Production tracking and optimisation platform.	https://www.cmexe.io/	- Just in time for lean construction - BIM software included - Integrates the supply chain, fabrication, logistics and installation in a single web-based hub. Complemented with cmBuilder, a 4D site logistics simulation software, and cmKnowledge for knowledge capturing and collaboration.
Dassault Systemes	Delmia	Construction simulation, real-time tracking capabilities, lean construction methodologies, modular construction, smart logistics and value-stream mapping.	https://www.3ds.com/products-services/delmia/solutions/construction-cities-territories/	- Dassault Systemes offers software for 3D product design, simulation, manufacturing and other 3D-related products - CATIA and 3DEXPERIENCE provide virtual twin technology - Claims to have off-site construction capabilities and optimisation, including reduced modular construction time by 70%
Donovan Group	AirBuildr	Construction design software package which dynamically generates engineering for portalised buildings. Automates modelling, loading, optimisation, design, and calculation engineering stages of a commercial construction project while setting a workflow.	https://donovangroup.com/airbuildr/	- Claim that the design process is at least 20 times faster than standard engineering methods (claim, unsupported by data or cases) - Scarce information on their website. No data was found on other websites.
Offsight	Offsight	Manufacturing project management software for the off-site construction and building components industry. The software streamlines collaboration between project managers, quality inspectors, production supervisors, and other project stakeholders to ensure factory projects stay on track.	https://www.offsight.com/	- Production and quality tracking - Factory reporting and auditing - Materials and inventory management - Labour tracking and timesheets

SiteDrive	SiteDrive	SiteDrive is a scheduling and project management software. It focuses on strong visual scheduling capabilities, dynamic communication, development collaboration, and tracking. SiteDrive claims to have digitalisation, modularisation, and takt production capabilities.	https://sitedrive.com/	- Developed by the construction company Fira - Success cases - Finland-based
Trunk Works Ltd.	Trunk	Software platform for off-site manufacturing and site assembly, giving real-time visibility of programs for manufacturers, clients, and project stakeholders.	https://trunk.works/	Trunk incorporates a dynamic scheduling AI that helps reduce waste and increase manufacturing throughput
Vizz technologies	MANUFACTON	Dynamic scheduling system (Cloud-based software) that helps manage the end-to-end off-site construction process. Standardise factory process. Standardise factory processes, leverage BIM models to generate bills of material, produce kits and assemblies, simplify collaboration, track materials and inventory, and coordinate deliveries to the job site.	https://www.vizztechnologies.com/modular-builder	- Presents cases - Used in 2,000+ buildings

Project management software suites

Company	Software name	Description	Web	Comments
Autodesk	Autodesk Construction Cloud	Provides designers, engineers, and contractors with a set of BIM and CAD tools supported by a cloud-based common data environment that facilitates project delivery from early-stage design through to construction.	https://www.autodesk.com/collections/architecture-engineering-construction/overview	- Create high-quality, high-performing building, and infrastructure designs with conceptual and detailed design tools - Optimise projects with integrated analysis, generative design, and visualisation and simulation tools - Improve predictability in the field with tools that maximise constructability and project coordination - Build: Connect field and project management workflows - BIM Collaborate Pro: cloud-based design collaboration software (Revit) - TakeOff: generate accurate estimates produced from integrated takeoffs and quantities
	Navisworks	Navisworks® review and coordination software to improve BIM (Building Information Modelling) project delivery.	https://www.autodesk.com.au/products/navisworks/overview?term=1-YEAR&tab=subscription	
	Revit	BIM software. Intelligent model-based method for planning, designing, constructing, and managing buildings and infrastructure.	https://www.autodesk.com/products/revit/features	- Includes automatic scheduling (doesn't specify how)
	Assemble	Integrate BIM data from design to Construction.	https://assemblesystems.com/	- Part of the Autodesk Construction Cloud - Can be dynamically connected with Primavera P6

Bentley Systems	SYNCHRO	4D scheduling and task management capabilities Project Management Suite.	https://www.bentley.com/en/products/product-line/project-delivery-software	- SYNCHRO Scheduler 2D Gantt chart project planning and scheduling software with an advanced CPM engine - Collaborative workflows based on project roles and permissions

	ProjectWise	Project management / BIM integration.	https://www.bentley.com/en/products/brands/projectwise	Seamless project collaboration and coordination

Deltek	Open Plan	Multi-project analysis, critical path planning, resource management, and risk analysis software.	https://www.deltek.com/en-au/products/project-and-portfolio-management/open-plan	- Complete suite with other project-based solutions to manage their clients, projects and finances - 30,000+ clients
	Deltek Acumen	Project analysis and schedule optimisation software.	https://www.deltek.com/en-au/products/project-and-portfolio-management/acumen	

Elecosoft	Powerproject	Project planning software, Project management, and risk analysis software.	https://elecosoft.com/products/powerproject/	Complete suite: Bidcon: Construction estimating software for BIM and construction cost management IconSystem: A cloud-based collaborative BIM software to record, specify, design, and manage building data. ShireSystem: Scalable CAFM software to manage multiple locations and assets Powerproject Vision: Web-based portal for managing Powerproject plans Available in stand-alone, enterprise, and cloud versions
	Site Progress Mobile	Site Progress Mobile allows site staff to update project progress at any time from any location, regardless of an internet or mobile connection – using a simple mobile app that synchronises the changes back to Powerproject.	https://elecosoft.com/products/powerproject/site-progress-mobile/	
	Powerproject Collaboration Cloud	Allows multiple users to work collaboratively across project files.	https://elecosoft.com/collaboration	
	Powerproject Vision	Enables users to view live project data across all projects by seamlessly connecting all projects and programs in one central location.	https://elecosoft.com/products/powerproject/powerproject-vision/	
	IconSystem	A cloud-based collaborative BIM software.	https://elecosoft.com/products/iconsystem/	

Microsoft Corporation	MS project	Project planning and scheduling.	https://www.microsoft.com/en-au/microsoft-365/project/project-management-software	- Extensively used - Integrable with other construction software - Integrable with MS Office/Teams - Proven cases

Oracle	P6 Enterprise Project Portfolio Management	Software for prioritising, planning, managing, and executing projects, programs, and portfolios.	https://www.oracle.com/au/industries/construction-engineering/primavera-p6/	- Extensively used - Integrable with other software - Proven cases
	Primavera Cloud	Project control and scheduling app for construction projects.	https://www.oracle.com/au/industries/construction-engineering/primavera-cloud-project-management/	- Extensively used - Integrable with other software - Proven cases - Oracle Construction Intelligence Cloud Service artificial intelligence (AI) and analytics solutions suite - Supports lean construction
	Oracle Aconex	Project management solution to manage the complete project lifecycle processes and connect teams. Fully configurable workflow templates and sub-workflows, bid and tender management, supplier documentation, cost management, quality, safety, and onsite collaboration.	https://www.oracle.com/au/industries/construction-engineering/aconex/	Mainly focused on document management

PMA Technologies	NetPoint	Dynamic & responsive project planning. The Graphical Path Method™ (GPM®) is an alternative to critical path method (CPM) that promotes rapid, collaborative, and informed project planning. GPM® shows the logical relationships of dated objects – such as activities, subtasks, milestones, and benchmarks – in a time-scaled network diagram with high visual impact.	https://pmatechnologies.com/netpoint/	- Dynamic critical path analysis - Multiple calendars - Custom non-workdays - Weather modelling
	Schedule MD™	Analyse metrics and determine schedule reliability.		

	NetRisk™	Accurately predict project completion dates and costs.		
Procore Technologies, Inc.	Project Management	Construction management software.	https://www.procore.com/en-au	- Construction Project Management Software Buyer's Guid - Plan includes unlimited users, unrivalled support, unlimited data storage and product enhancements at no additional cost
	App Marketplace	Open App marketplace including third party development, 300+ integrations, apps, and services.	https://marketplace.procore.com/categories/scheduling	
	Workforce Planning	Resource management solutions spreadsheets, whiteboards, and databases to develop an all-in-one platform that helps contractors with labour scheduling, forecasting, communications, certification tracking, and labour analysis.	https://www.procore.com/en-au/workforce-planning	
Trimble Inc.	Trimble Connected Construction	Multiple software solutions to plan, design and engineering, program and project management, fabricate and construct, and operate and manage.	https://construction.trimble.com/en/	- Multiple software for different industries - Success cases
	ViewpointOne construction management suite	Construction management, job costing, project management, service management, employee management, and data & reporting.	https://www.viewpoint.com/en-au/viewpointone	Proclaimed as a solution for modular projects
	Tilos	Scheduling and planning software provides a simplified, visual look at the construction project through a powerful linear scheduling view.	https://projectsight.trimble.com/	

	ProjectSight	Trimble's next-generation project management solution built for collaboration.	https://projectsight.trimble.com/	
	Viewpoint Spectrum	An all-in-one web-based construction ERP and a component of Trimble Construction One.	https://www.viewpoint.com/en-au/viewpointone	

Project management software

Company	Software name	Description	Web	Comments
Doxel	Doxel Schedule	Real-time construction optimisation platform. AI-powered project controls.	https://www.doxel.ai/doxel-schedule	Doxel provides an overview and project forecasts by contextualising project data across sites, BIMs, schedules, and budgets
Exigo	Vico Office – Vico Control (scheduling)	Comprehensive solution, including 4D scheduling and resource management.	https://vicooffice.dk/en/	- Denmark based (some things not translated) - Cost planner - Document controller - LBS manager - Production controller - Schedule planner - Takeoff manager - Work package manager - Web services
InEight, Inc.	InEight	Integrated construction management software.	https://ineight.com/	- Schedule, risk and design - Estimating and project cost management - Safety, quality and commissioning - Field execution management - Connected analytics - Collaborative document management - Capital and contract management - Virtual design and construction
Schüco	PlanToBuild	Comprehensive software for construction project management. Includes scheduling, task management, daily construction reports, defect management and	https://plantobuild.online/en/	- Germany based - Comprehensive solution

		reporting, and multi-project management functions.		
StratusVue	PlansandSpecs	StratusVue PlansandSpecs is an integrated platform to manage projects from design to operations. Project manager, cost manager, document manager, bid manager, and BIM software.	https://stratusvue.com/products/plansandspecs/#projectmanagement	- Multiple projects in the USA
Veyor Digital	Veyor	Cloud-based scheduling and planning software serving the construction industry designed to optimise on-site operations.	https://www.veyordigital.com/	- Lendlease is already a client. Used it for the Melbourne Connect project. - Clients: leading contractors in Australia
VisiLean	VisiLean	Lean and BIM integration in a construction management system.	https://visilean.com/	- Dynamic planning - Not present in Australia - HR and admin, procurement, design, safety, inventory, quality, designs, and information

Complementary software

Company	**Software name**	**Description**	**Web**	**Comments**
Algo'Tech Informatics	VISION	Complete studio.	https://www.algotech.vision/	France-based, mainly focused on BIM
Kahua	Kahua	Collaborative construction program and project management software.	https://www.kahua.com/	Lendlease is already a client
Vertex Systems	Vertex BD Building Design Software	BIM Software for prefab and modular construction.	https://vertexcad.com/bd/prefabricated-and-modular-construction/	BIM focus, no scheduling or project management features

Small to Medium client focus

Company	Software name	Description	Web	Comments
BrickControl	BrickControl	Cloud-based construction management software.	https://www.brickcontrol.com/	- Spain-based - SME focus - Client: Acciona
Buildertrend	Buildertrend	Construction management software.	https://buildertrend.com/	SME focus
BuildIT Systems Corp.	BuildIT	Construction Scheduling Software.	https://www.builditsystems.com/	SME focus
CO	CoConstruct	Construction management software for custom home builders and remodelers.	https://www.coconstruct.com/	No evidence of big clients
Contractor Foreman	Contractor Foreman	Small and medium trade and general contractors management software.	https://contractorforeman.com/	SME focus
ECI Software Solutions	BuildTools	Complete industry-specific ERP software that makes doing business easier for small and medium-sized businesses.	https://www.ecisolutions.com/en-au/	SME focus
Fergus	Fergus	Job management software for trades and service businesses.	https://fergus.com/en-au/	- Local product - SME focus
Hyphen Solutions, LLC	BuildPro	Supply chain construction management software for home builders.	https://www.hyphensolutions.com/info/products/buildpro/	SME focus
Infinity Platforms	HQ Platform	SME all-inclusive construction software.	https://infinityplatforms.com/	- No experience or client testimony reported - SME focus
JGID	JGID	Job Management Software for High-Risk Industries.	https://jgid.com/	- Local product - SME focus
Jobber	Jobber	Job management and customer service software.	https://getjobber.com/	Home service businesses focus
JobTread Software, LLC	JobTread	Construction management software for Home Builders (spec and custom), Remodelers, General Contractors, Specialty Contractors, and Commercial Contractors.	https://www.jobtread.com/	Work management software. SME
Payaca	Payaca	Job management software.	https://www.payaca.com/	- SME focus - UK-based

PlusSpec	PlusSpec	PlusDesignBuild: Virtual Design Construction & Estimating Software.	https://plusspec.com/	4D BIM Scheduling
ProPlanner	ProPlanner	Construction scheduling and planning.	https://www.proplanner.build/	- Promoted as an alternative to MS Project and Primavera - No evidence of big clients
Remato Solutions	Remato	All-in-one Construction Software.	https://remato.com/en-au/	SME focus
Sage	Sage Construction and Real Estate	Field-based project management.	https://www.sage.com/en-us/sage-construction/	Mainly focused on workflows
Tradify	Tradify	Job management app.	https://www.tradifyhq.com/au	SME focus

Other

Company	Software name	Description	Web	Comments
3D Repo LTD.	3D Repo	Manage Building Information Modelling (BIM) data during design, delivery and operations.	https://3drepo.com/	BIM collaboration software
ACCA software S.p.A.	PriMus KRONO	Construction scheduling software.	https://www.accasoftware.com/en/construction-scheduling-software	No evidence of big clients
	Edificius	IFC-OpenBIM.	https://www.accasoftware.com/en/architecture-design-software	Italy-based
BuildScan	BuildScan	Collaborative defect and task management.	https://www.buildscan.co/	Focused on project defects
Dado	Dado	Integrates Project management and Document Cloud Platforms, such as Autodesk Build or BIM 360® projects, Dropbox, google drive, box, Onedrive, and MS Project.	https://projectdado.com/	Voice-driven document search engine for construction
Digi Corp srl	JOIN	4D BIM software module for time management.	https://www.digicorp.it/en/join/	Italy-based, mainly focused on BIM

Future Network Development (FND)	ISETIA	Complete project management platform.	https://isetia.com/	- Poland-based - Not available in Australia
Intelliwave Technologies ' SiteSense®	SiteSense	Identification and tracking of construction materials, equipment, and tools.	https://www.intelliwavetechnologies.com/	Can be integrated with other software
Kreo Software Ltd	Kreo 2D Takeoff	- AI-powered 3D BIM quantity takeoff software for precise, fast, accurate cost estimates. - AI-powered construction takeoff and estimating software tools to help quantity surveyors, estimators and contractors.	https://www.kreo.net/	AI-assisted construction software solutions. Includes scheduling but is not focused on real-time project management.
Novade	Novade	Management software for property developers.	https://www.novade.net/	Construction management platform to improve quality, productivity, and safety
Plexos	Plexos Project	Lean project management.	https://plexosproject.com/index.php	- Easily create complex schedules integrating BIM models, cost and budget databases in the cloud - Not available in Australia
StayOnHire	StayOnHire	Rental Management.	https://www.stayonhire.com/au	- Designed for construction, equipment and plant hire companies that manage heavy equipment hire or civil construction projects - Local product
WebFM	OmTrak	Manages critical building information and allows easy project collaboration.	https://www.omtrak.com/	Client: Lendlease
Wiseworking	ConstructionID	Project management software that combines Quality, OH&S and document control.	https://constructionid.com/	Local – developed for the Australian construction and building maintenance industries and is serviced in Australia

Work management software

Company	Software name	Description	Web	Comments
Aprika Business Solutions Ltd.	Mission Control	Salesforce native Professional Services Automation (PSA) and Project Management SaaS.	https://aprika.com/missioncontrol/	
AroFlo Innovations Pty Ltd.	AroFlo	Job Management software.	https://aroflo.com/	Local product
Assignar, PTY LTD	Assignar	Schedule crews and equipment, manage compliance quality and safety, and monitor progress from a single platform.	https://www.assignar.com/au/	Resource utilisation optimiser and scheduler
Atlassian	Jira	Project management tool for agile teams, customisable for any type of project.	https://www.atlassian.com/software/jira	- Mainly focused on Software project management (AGILE) - Trello's same developers
Breez, LLC	Breez Workforce Management	Workforce Management.	https://www.breezworkforce.com/	
Bridgit	Bridgit Bench	Workforce planning software for general contractors.	https://gobridgit.com/	
Citrix	Wrike	Work management software.	https://www.wrike.com/	
ClaritySoft	Clarity CRM	Cloud-based CRM software.	https://claritysoft.com/project-management-software/	A CRM platform expanded into a project management SAAS
ClickUp	ClickUp	Project management tools, including Docs, Reminders, Goals, Calendars, Chat, scheduling, assigned comments, and custom views.	https://clickup.com/	Work management software
EDWARD	EDWARD Suite	Decision Management System.	https://www.edward-suite.com/en	Decision making platform aiming to help Transformation Office and consulting firms manage their complex projects portfolio
EnsureFlow	EnsureFlow	Job Management software.	https://www.ensureflow.com/	Local product
EV20 Consulting Group	Drive Lynx	Organisational workflow.	https://ev20group.com/drive-lynx/	Local product
Float	Float	Resource management platform.	https://www.float.com/	

JOBPROGRESS, LLC	JOBPROGRESS	Customised Job & Workflow Manager.	https://www.jobprogress.com/	
KreativBricks	KreativBricks	Labour and material tracking.	https://kreativbricks.com/	KreativBricks was created with the Indian real estate and construction industry in mind
monday.com	monday.com	Project Management Software.	https://monday.com/construction	Work management software focused on something other than scheduling
One2Team	One2Team	Multi-solutions platform for visual collaboration: strategy, planning and project creation and execution.	https://one2team.com/	Mainly a work management platform
PARASCADD	PRODOCS	Document Management System.	https://parascadd.com/products/prodocs-electronic-document-management-system/	Document Management System (DMS) manages, tracks, and stores digital documents
PLANFRED GmbH	PLANFRED	Collaboration and document sharing software.	https://www.planfred.com/en/	
Planview	Clarizen	Enterprise work management solution for PMOs and professional services delivery teams.	https://www.planview.com/products-solutions/products/clarizen/	
Project on Track	Project on Track	Construction Project Management Software.	https://www.projectontrack.net/	- Construction Management, Contract Management, Resource Management, Document Management, Dashboard and Reports, and Cloud-Based Scalable System - Local product
Salesforce	Salesforce Sales Cloud	CRM platform.	https://www.salesforce.com/au/products/sales-cloud/overview/	Work management software focused on something other than scheduling
Smartsheet Inc.	SmartSheet	- Scale from a single project to end-to-end work management - Collaboration tools that keep teams aligned, including intelligent workflows that drive productivity, to end-to-end solutions for content and resource management.	https://www.smartsheet.com/	Work execution platform (not specific for construction). Project schedule with an interactive Gantt chart and manage all aspects of a construction project in one central information hub
SINC	SINC	Timecard And Location Tracking App.	https://sinc.business/	Work management software. SME
Stilog	Visual Planning	Visual scheduling & planning software to track all types of resources.	https://www.visual-planning.com/en/	- Work management software - Website not working correctly

TargetSkills	PlanningPME	Managing tasks and resources software.	https://www.planningpme.com/	
Toggl Plan	Toggl Plan	Team project and work planning tool.	https://toggl.com/plan/index	Project management and work management software
V-PLAN	Realtraker	Construction project planning, estimating, customer management, and subcontractor scheduling.	https://realtraker.com/us/	Not available in Australia
Vizerra SA	Revizto	-Unified access to a project's data both for 2D and 3D workflows. - Collaborative Clash Management.	https://revizto.com/en/	BIM collaboration software
WIZZCAD	WIZZCAD	Management, operations and maintenance software.	https://wizzcad.com/en/	Not specifically used for scheduling

CHAPTER 6 CONTENTS

CHAPTER 6: SYSTEMS INTEGRATION IN PRODUCTISED BUILDING PROJECTS

Osama Hussain, Linna Geng and Robert Moehler

6.1 Executive summary

6.1.1 Systematic literature review

The building sector has recently seen a surge in new technologies and digitalisation, leading to new levels of complexity. The growing market for productised building projects requires effective systems integration, which combines system elements or components to create a product or service. This report identifies 5 research clusters in this area: 1) building information modelling (BIM) and information communication technologies (ICTs); 2) design and interface management; 3) interorganisational projects and innovation; 4) collaboration and modularity; and 5) critical success factors (CSFs) and manufacturing.

Key findings for systems integration in productised building projects include the following:

- Using BIM and ICTs requires maintaining an integrated repository for all building component workflows and information.
- Coupled or decoupled design supports collaboration by coordinating and cooperating within a modular or integral organisation.
- Systems integration in productised building projects promotes interorganisational innovation.
- The ‘V’ model offers a framework for systems integration practices across various project phases.
- Emphasising critical success factors, such as robust design and early design freeze, close collaboration, effective communication, and early stakeholder engagement, is essential for project success.

Further, modularity and integration play key roles in achieving collaboration throughout the productised building project life cycle. The characteristics of different systems integrators and their roles in supporting collaboration are essential for success. Three recommended strategies include:

- creating a project-based learning platform
- implementing coupled and decoupled thinking in integration
- developing and sharing professional systems integration knowledge.

Recommendations for improvement are divided into strategic-long term and process improvement-short-term goals.

- Long-term goals include increasing end-user awareness, investing in long-term partnerships, sharing risks and benefits, collaborating on platform-based designs, and standardising interfaces.
- Short-term goals involve increasing the agility of the gates system, establishing a common data environment (CDE), and developing in-house productisation capabilities.

Future research should focus on end-to-end process mapping and analysis to clarify the current state, identify areas for improvements and automation, and detect any productisation soft gates.

6.2 Introduction

We examined and analysed system integration, modularity, coupling and decoupling, and interface management for productisation through a literature review to better understand the potential of a productised approach to building delivery.

1. *Definition of systems integration, interface and interface management, modularity and decoupled system and coupled system* are discussed and contextualised for productisation.
2. *The benefits of productisation and respective implementation in the construction industry are reviewed in the literature, standards and industry consultation. The discussion focuses on critical success factors, complexity implications, and construction components that have been successfully modularised and implemented in the delivery*.
3. *System integration of productisation in the project lifecycle implies longitudinal, horizontal, and vertical integration of planning, design, and construction delivery constraints that can enable associated benefits*.
4. *In the systematic literature review, 5 clusters are significant to manage system integration of productisation in the construction industry:*
    a. Cluster 1: BIM and ICT as a digital integration strategy leading to either specialisation of productisation as a service, or a platform as modular approach with an expertise and integration focus.
    b. Cluster 2: Design and interface management (IM) is a project management approach integrating both digital and key modular interfaces physically (prototypes for systems interfaces) through increased stakeholder engagement and component control.
    c. Cluster 3: Interorganisational projects and innovation focuses on the complexity, innovation, and systems engineering aspects of interorganisational projects in productised construction, emphasising the role of systems integrators in achieving innovation through effective coordination and implementation of recombined and replicated systems or production processes.
    d. Cluster 4: Collaboration and modularity pertains to 'modularity', 'platforms', 'collaboration', 'lifecycle', and 'product development'. BIM and ICTs advancements are supporting systems integration and collaboration technologies that facilitate the creation, management, dissemination, and use of information throughout the entire product and project lifecycle, integrating people, processes, systems, and information more effectively. The 'V' model demonstrates the systems integration and collaboration required throughout the project lifecycle. Modularity is necessary to ensure productivity and optimal product family design, because it allows for product platforms and modules, and identifies components for potential integration.
    e. Cluster 5: Critical success factors (CSFs) and manufacturing encompasses the key concepts of 'CSFs', 'manufacturing', and 'integration'. Manufacturing – often seen in productised construction, prefabricated construction, and off-site construction – is a group of digitally controlled additive processes, which involve widespread application of automation technologies and the adoption of lean construction. Critical factors such as interoperability, legacy systems, and human-system interaction are key to improve systems integration performance.
5. *The Project lifecycle phases do change from process, role, and organisational emphasis/capabilities.*

Details about systematic literature review and roadmap design, review of related standards and analysis leading to the roadmap have been consolidated in Appendix A.

6.3 Aims, methods, and sources

This systematic review summarises the current state of productised building projects that have been integrated into systems. It defines terms, explores theories, identifies approaches, and explains key concepts, to address the growing complexity in productised building design, planning, and delivery.

We sourced literature through a keyword search in the Scopus database, using the terms 'systems integration' or 'interface management' combined with 'construction' or 'Building'. The search was limited to English-language publications from 2010 onwards and produced 30 papers eligible for review. These papers were then analysed for definitions, theoretical foundations, and approaches, and we conducted a co-occurrence analysis of keywords.

6.4 Background

The construction industry has seen a rise in the popularity of productisation, which involves analysing customer needs, defining, and combining elements to create standardised products for the mass market (Mustonen et al. 2019; Wirtz et al. 2021). The industry is intrinsically a loosely coupled system in which it is difficult to develop components and systems that are suited to the situations at specific sites because of a lack of clarity in specifications, lack of consistency, and the unpredictably changing environment (Dubois and Gadde 2002). Despite the inherent complexity of construction projects (such as the fragmented nature, unique elements, and multidisciplinary teams involved), productisation has become a key focus due to the benefits it can provide in terms of data requirements, workflows, and value generation (Boton et al. 2016; Kabirifar and Mojtahedi 2019; Wuni et al. 2022). Adoption of productisation, made possible by virtual technologies, can greatly benefit the construction industry by enabling interoperability of data and workflows throughout the project lifecycle, leading to faster and more efficient building design and construction (Lassila 2021). For instance, Mansoori et al. (2022) applied the concept to BIM implementation to ensure process efficiency and data integrity among building systems. However, productised construction projects can present challenges in developing components and systems that fit the overall building system and are suitable for specific sites (Dubois and Gadde 2002; Mansoori et al. 2022). Key components of productisation include integration-ready modules, design information integration, and streamlined workflows (Lehtovaara et al. 2021). Thus, while productisation offers opportunities to streamline construction processes, it also requires an integrated systems approach throughout the project lifecycle.

Systems integration is the process of coordinating and combining individual components of a system to work together. It was first established and utilised in the aerospace and defence industry in the 1950s, and has since become a discipline of systems engineering. For example, Ramo-Wooldridge Corporation served as a system integrator for the Atlas project, coordinating numerous contractors and developing thousands of subsystems (Whyte 2016). The importance of systems integration has been recognised in managing large and complex construction products and systems (Shen et al. 2010), with case studies such as the London 2012 Olympic and Paralympic Games (Davies 2017). This is especially true for productised construction projects, where fragmentation, complexity, and loosely coupled systems make integration essential for the design, planning, and coordination of multiple interdependent components (Whyte and Davies 2021). However, there has been limited exploration of the theories, approaches, and knowledge streams for systems integration in productised construction projects.

6.5 Definitions

6.5.1 Systems integration

Integration refers to the process of bringing together smaller components into a single functioning system. In conventional construction, it involves coordinating construction activities (Demirkesen and Ozorhon, 2017). With the rise of productised technologies and increased complexity in construction projects, the concept of systems integration has become increasingly important. According to ISO/IEC/IEEE (2015), **systems integration** involves *combining iteratively various elements to create a complete or partial system configuration for a product or service*. Systems integration has its roots in systems engineering and has been applied to both technical and managerial aspects of construction projects. For example, in the London Crossrail Project, systems integration is seen as a dynamic process that balances stability and change while responding flexibly to changing conditions in complex projects (Muruganandan et al., 2022). To better understand the definition and application of systems integration in productised building projects, a Table 1 presents a review of various definitions.

Table 1. Descriptions of systems integration in building projects.

No.	Definition	Unit	Author
1	Systems integration can be conceptualised as *a dynamic process of balancing stability and changes while responding flexibly to changing conditions in complex projects.*	London's Crossrail Project	Muruganandan et al. (2022)
2	It defines a systems integration process that *links design, planning, manufacturing, and inspection so that discrepancies may be identified and monitored often based on open data principles.*	Aircraft	Li et al. (2020)
3	Five levels of system integration were proposed: *remote, touching, connected, meshed, and unified.*	Infrastructure Management	Zhang and El-Gohary (2017)
4	Effective *integration* between virtual models and the physical construction should be able to *communicate design information*; *capture, and document as-built information; track construction progress and, control building components* in the constructed facility.	Cyber-physical System Architecture	Akanmu and Anumba (2015)
5	At a lower level of complexity, *system integration combines various components and subsystems jointly performing multiple functions into an entire system or platform to meet a specific client's requirements*, including services provided during the operational life of a system.	London 2012 Olympics and Paralympics Games	Davies and Mackenzie (2014)
6	*System integration enhances the value, such as cost reduction, quality, and productivity, added in the whole network of shareholders throughout the building lifecycle*.	Construction Information Systems	Tatari and Skibniewski (2011)

Summary of systems integration in building projects:

- dynamic balancing of stability and change in complex projects bringing flexibility (Muruganandan et al. 2022)
- linking design, planning, manufacturing, and inspection with open data principles (Li et al. 2020)
- 5 levels of integration (remote, touching, connected, meshed, unified) (Zhang and El-Gohary 2017)
- effective communication between virtual and physical construction to track progress and control building components (Akanmu and Anumba 2015)
- combining components and subsystems to meet specific client requirements (Davies and Mackenzie 2014)
- enhancing value for stakeholders throughout the building lifecycle (Tatari and Skibniewski 2011).

6.5.2 Interface and interface management

Research on systems integration reveals a project can be considered a system of interdependent parts that must be integrated to achieve an overall goal. The need for system integration can be described as the extent to which many interdependent components must be fitted together through effective ***interface management*** and adjusted to each other for the project to become available and to yield the output for which it was designed. Interface and interface management play a vital role in system integration within construction projects, which can be considered as:

Interface – "*the boundaries and connections among various project phases, systems, tools, people, organisational, physical elements, and other things"* (Sha'ar et al. 2017).

Interface management – *"management of communication, coordination, and responsibility across a common boundary between 2 organisations, phases, or physical entities which are interdependent"* (Fellows and Liu 2012).

During the systems integration process, 3 types of interfaces are discussed (Figure 1).

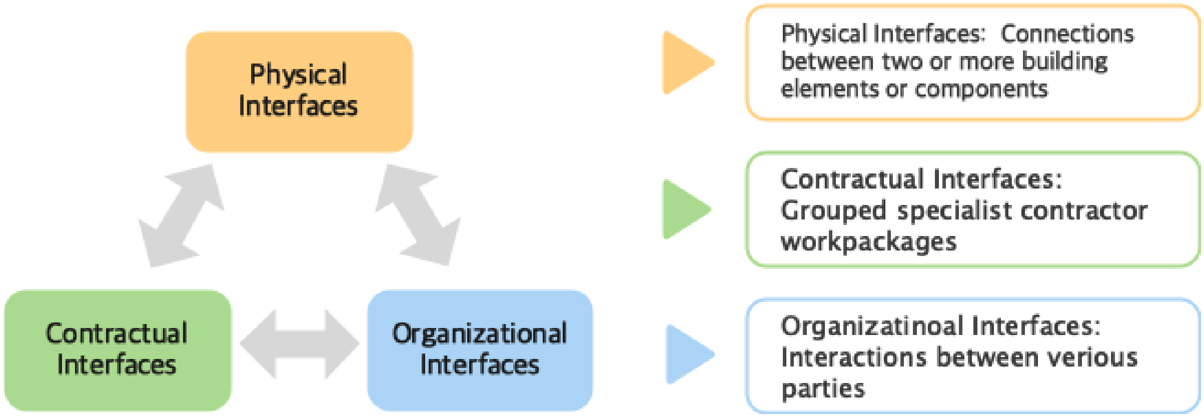


Figure 1. Interfaces within building.

Physical interfaces are inevitable in construction projects, such as the typical interface between precast concrete and curtain walling. It is highly dependent upon the detailed design. Standardising designs – i.e., using standard components or common platforms in varying arrangements for a program of similar projects – may reduce the number of interfaces.

Contractual interfaces occur when work elements are grouped into distinct work packages to suit the design information availability. They are expected to be agreed on at an early stage and managed throughout the project.

Organisational interfaces include the relationship between individuals and parties involved in the construction process from initial conception to final handover. Efficient management between these parties is essential for integrating the building system, and successful implementing a project.

6.5.3 Product modularity

The productised approach aims to balance customisation with efficiency, cost, and quality of mass production (Bertram et al. 2019). Industries construction (IC), off-site construction (OSC), and productisation are gaining recognition for their benefits (Wuni, Shen, and Darko 2022; Hwang, Shan, and Looi 2018). Productisation has been around for many decades, emerging through different terminologies and taxonomies (Goulding and Rahimian 2019).

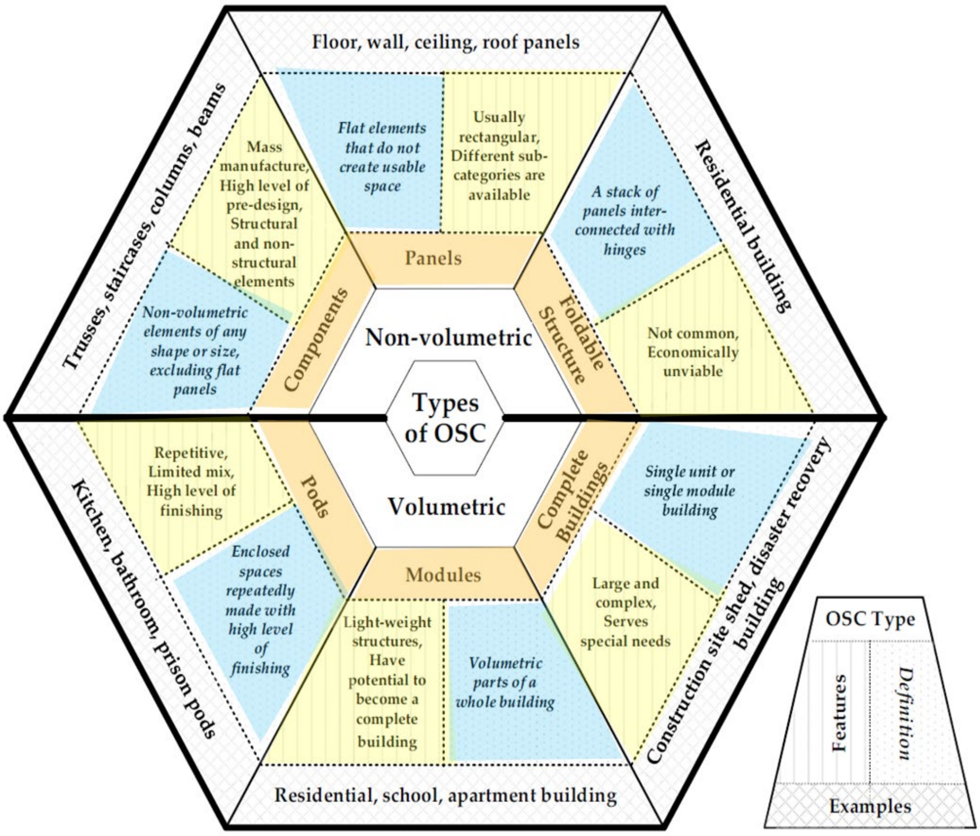


Figure 2. Productisation/OSC typologies (Ginigaddara et al. 2021).

Figure 2 depicts the productisation / OSC typologies and definitions, which can be classified as volumetric (pods, modules, complete buildings) or non-volumetric (components, panels, foldable structure), (Ginigaddara et al. 2021). ***Product modularity*** is *an attribute of complex systems that advocates designing structures based on minimising interdependence between modules and maximising interdependence within them that can be mixed and matched to obtain new configurations without loss of the system's functionality or performance* (Campagnolo and Camuffo 2010). It has been widely applied in manufacturing but not in construction, precluding this industry from its benefits. In general, modularity means a system can be decomposed into parts or modules. It has been deployed to simplify product design by partitioning the product into chunks that can be independently developed, or to simplify production by combining a large number of small components into larger chunks or subassemblies (Baldwin and Clark 1997; da Rocha and Kemmer 2018; Sako and Murray 1999). Product modularity can improve product quality and production efficiency to achieve high product variety and high volume (da Rocha et al. 2015).

To define productised building parts via product modularity, 'module' is used to describe 3 typologies, based on Gosling et al. (2016). As Table 2 shows, a module can be simplistically equated to a subassembly produced off-site. However, the lack of integration between such product and process design, which is typical in construction, should be emphasised.

Table 2. Characteristics of typologies (Gosling et al. 2016).

	Volumetric modules produced off-site (Typology I)	Non-volumetric modules produced off-site (Typology II)	Non-volumetric modules assembled on-site (Typology III)
Number of modules	Small	Medium	Large
Number of interfaces	Small	Medium	Large
Number of parts forming each module	Large	Medium	Small
Design approach	Modular (design modules)	Traditional or modular (design modules)	Traditional or modular (design modules)

In productisation, Kuula et al. (2018) view set-based design as a delivery-oriented approach that enables components to meet most functional requirements. The integration of design information and material flows into the takt of production has proven critical to productisation (Lehtovaara et al. 2021). According to Shingo (1989), flow in production refers to a chain of events, and the difference between process and operation is crucial to production theory. As shown in Figure 3, the production flow consists of 2 axes – process flow and operations flow – which together create a flow network (Shingo and Dillon 1989). While process flow refers to the movement of products down the production line, operations flow refers to the activities performed by operators and equipment at workstations. In manufacturing, these axes are often separated to enable detailed production improvement. However, in construction, trades and equipment move through locations while operations flow advances diagonally as trades perform activities (Lehtovaara et al. 2021).

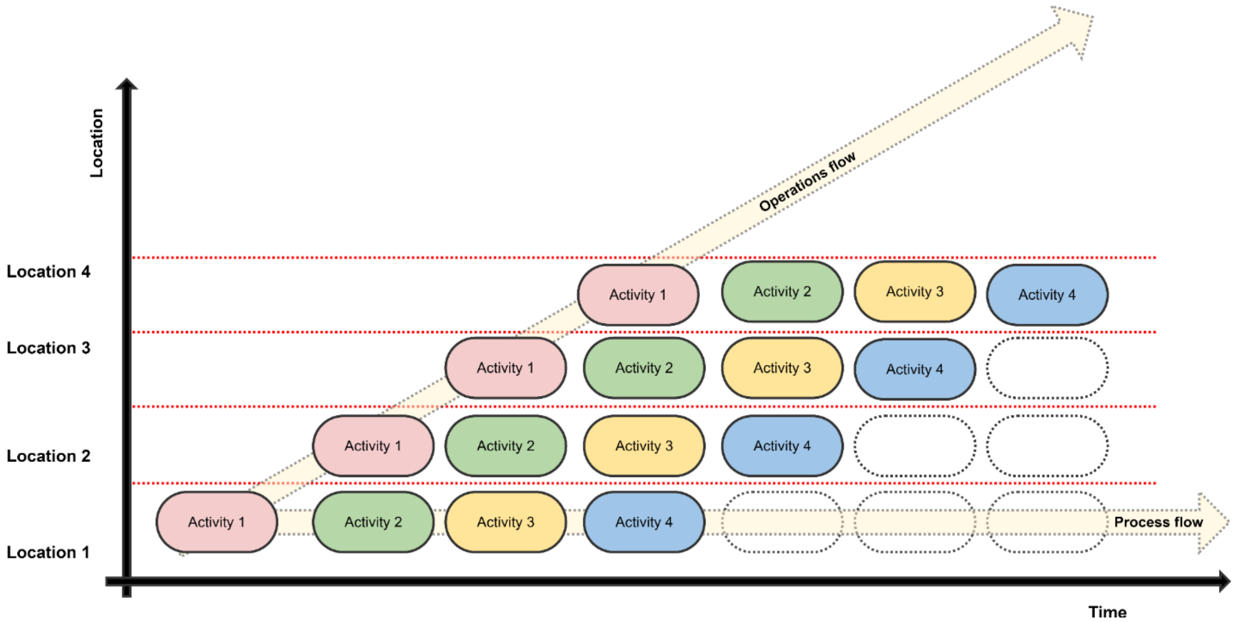
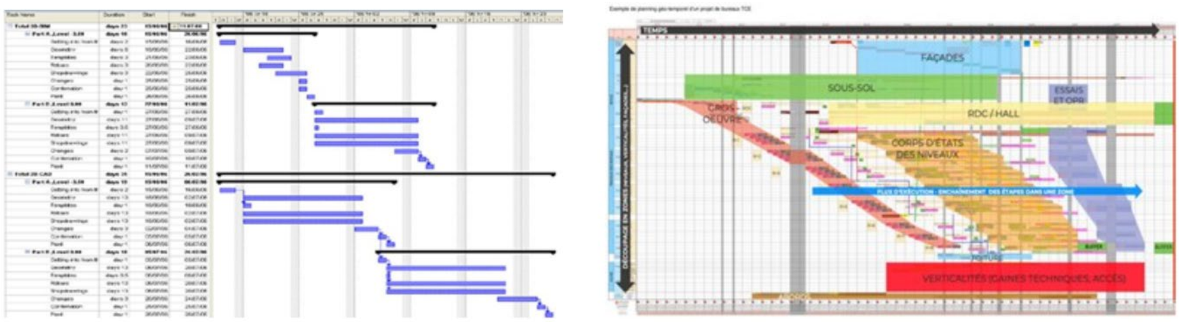


Figure 3. Relationship of process and operations flows in construction (adopted from Lehtovaara et al. 2021).

Using 5 buffers can improve construction production flow: time, space, capacity, inventory, and plan. Capacity buffers should be prioritised for better performance and shorter project duration. The critical path method (CPM) has limitations in maintaining production flow and has been criticised for producing complex schedules. Location-based planning tools such as line of balance (LOB), location-based management system (LBMS), and takt production have been developed to overcome these limitations. LBMS is a hybrid of location-based methods and CPM, while takt production aligns repeated processes to enable flow-efficient production. The objective of takt production is to improve flow holistically by favouring capacity buffers and maintaining constant takt time. Figure 4 shows a comparison of a typical Gantt chart (CPM-based) versus time location planning (LBMS based), where lines represent tasks in the Gantt chart and task sequence in the time location diagram.



Gantt Chart

Time-Location Planning

Figure 4. Gantt chart versus time location planning.

Modular integrated construction (MIC) is a core strategy for productisation, incorporating multi-trade assemblies, standardised interfaces, and generative variants. MIC presents significant opportunities for improving project performance when effectively applied. However, the construction industry is still struggling to achieve high degrees of modularisation due to various challenges (Wuni and Shen 2020; Choi, Chen, and Kim 2019). These challenges include owner tendencies to resist new technologies, transportation and logistics issues, contractor and fabricator capabilities, absence of standards, laws and regulations, lack of specialised software or hardware, technical training shortages, and expensive specialist education and design and construction culture (National Institute of Building Sciences 2014; Choi, Chen, and Kim 2019; Qi, Costin, and Razkenari 2019). To better understand the success criteria and address the challenges of MIC, critical success factors (CSFs) for MIC and productisation were identified and analysed by Wuni, Shen, Osei-Kyei (2020), Wuni, Shen, and Sar (2020), and Wuni and Shen (2020). These interrelated factors can influence each other and were modelled using the Vensim software tool. The resulting casual loop model for the CSFs consists of the variables (CSFs), the linkages between them, the signs on the links (positive/negative), and the loop/system direction (Figure 5).

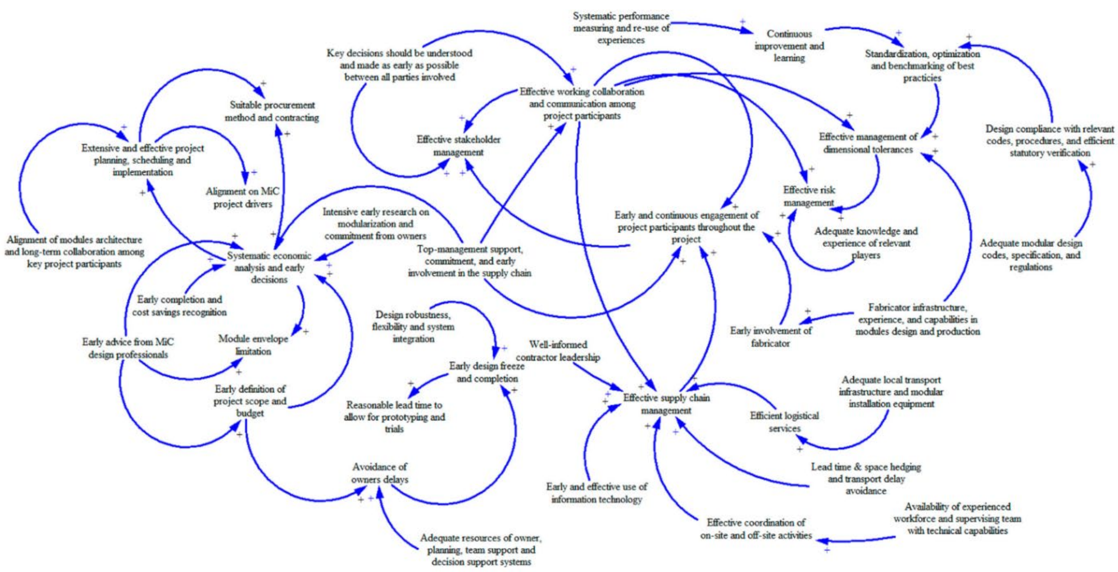


Figure 5. Casual loop modelling for the CSFs.

Successfully managing the conception and planning stages is critical to overall project success. Critical success factors are listed in Figure 6.

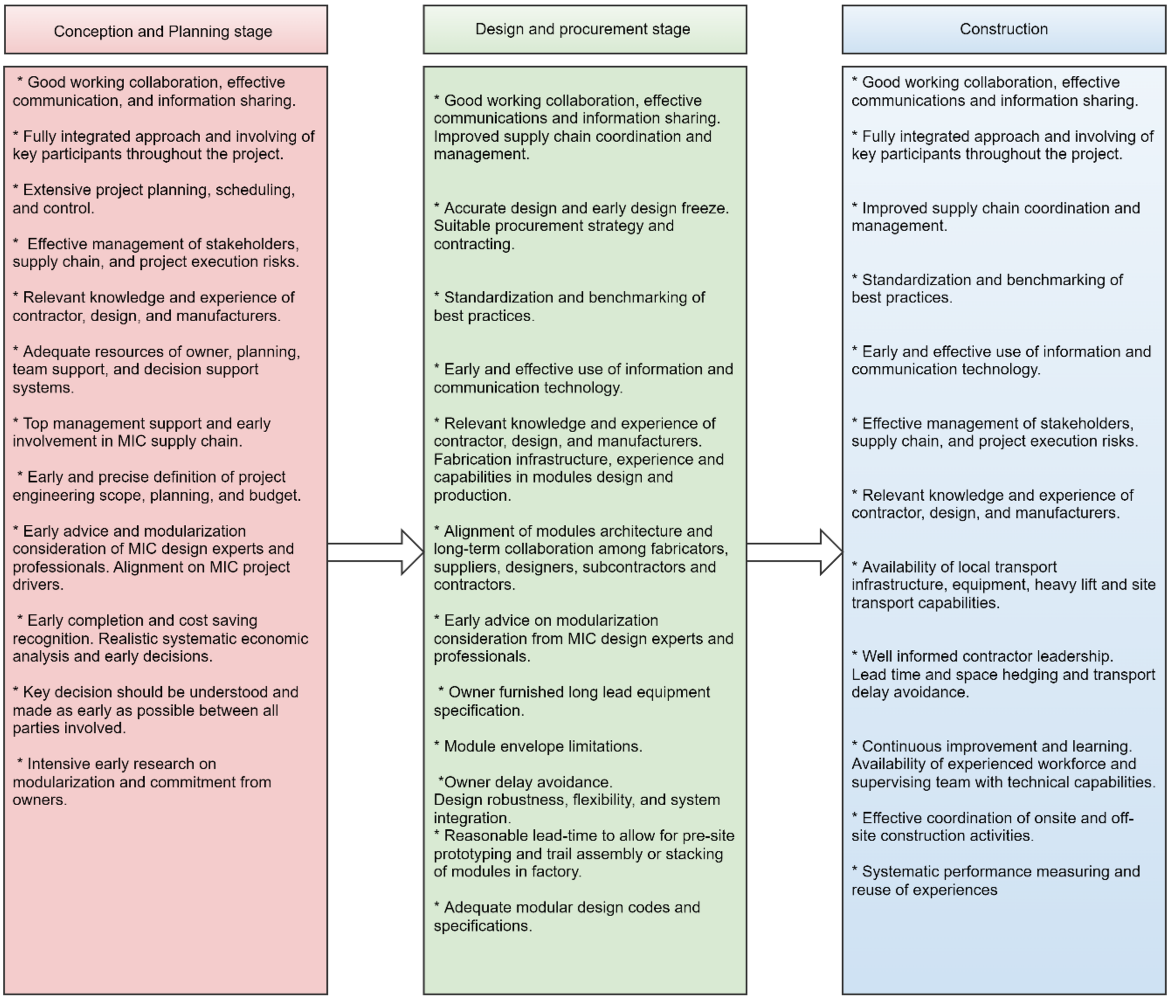


Figure 6. Critical success factors (CSF) for MIC and productisation (adopted from Wuni and Shen 2020).

6.5.4 Decoupled system and coupled system

In recent productised building projects, considering integration and capability implications has led to a strategic approach to coupled and decoupled building systems (Cheng et al. 2018).

In a **decoupled building system**, designers strive to keep the features of building systems distinct and independent from each other (later leading to modules as components or subsystems). Components are designed independently, with their own data and workflows, that can be developed, executed, and further tested, allowing for flexibility as design criteria change.

In contrast, in a **coupled building system**, designers assume design criteria will change less, and design requirements are closely tied to each function. Many building projects utilise a hybrid approach, combining both decoupled and coupled systems, depending on the specific requirements and strategic considerations.

It is common for some functions to have stringent design criteria while others are overdesigned, resulting in a mixed design between the 2 types.

6.6 System integration process in productised projects

Integrating systems in productised building projects usually incorporates the phases of conceptual design, detailed design, manufacturing at factories (production), transportation, assembly on site, and handover to operation (Figure 7). It is facilitated by advancements in information technology, such as BIM and virtual design and construction (VDC). These technologies support the collaborative and multidisciplinary development of a data-driven project delivery process by enabling an integrated digital model of building components and systems. BIM facilitates planning and communication across design, manufacturing, and construction phases by providing a comprehensive and accurate representation of the building to manage different types of interfaces efficiently (Jones et al. 2021).

Systems integration in productised constructions can be classified as vertical, horizontal, and longitudinal.

Vertical integration refers to managing interfaces between project phases. The employed strategies, proposed by (Nam and Tatum 1992), include acquisition-based approaches, non-contractual methods of alignment, contracts as vertical coordinating mechanisms, and integration of information.

Horizontal integration involves coordinating different specialists, such as architects and engineers, or parties to deliver the required and complementary products and services at the same project phase. Horizontal integration requires the efficient flow of information between the specialists and accelerates the construction process with disciplinary knowledge (Tee et al. 2019).

Longitudinal integration encompasses project-to-project learning opportunities from one-off projects (Addis 2016) and ensures the smooth flow of knowledge and information over time, enabling productivity gains from continuous improvement processes and product improvements (Thuesen and Hvam 2011).

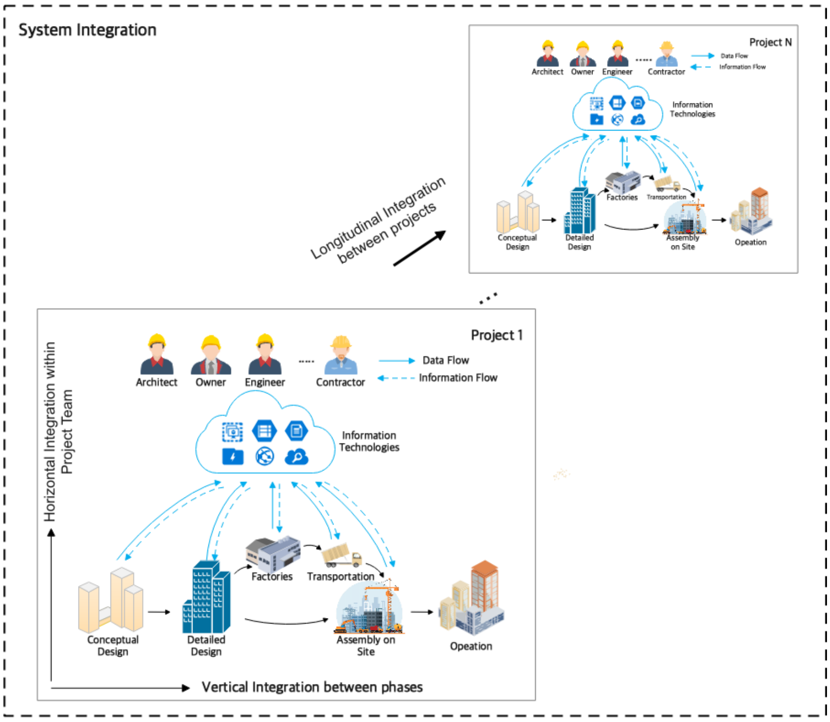


Figure 7. System integration in productised building projects.

Table 3 shows the relationship between interface management and system integration.

Table 3. The relationship between interface management and system integration.

Integration dimensions		Interface types
System integration	Vertical integration	Physical interfaces Contractual interfaces Organisational interfaces
	Horizontal integration	Physical interfaces Contractual interfaces Organisational interfaces
	Longitudinal integration	Physical interfaces Contractual interfaces Organisational interfaces

6.7 Project lifecycle system integration 'V' model

In recent years, systems integration has become increasingly important in productised construction projects due to their complexity in achieving satisfactory project performance (Shen et al. 2010). The lifecycle-based 'V' model has been adopted as a theoretical foundation for systems integration in existing construction studies. The model brings together 2 main levels of systems integration: diverse knowledge and cyber-physical components (Davies and Mackenzie 2014) (Figure 8). The role of an integrator – who specialises in bringing together components and ensuring they function together – is crucial in complex projects to coordinate network of suppliers and design overall system. Figure 8 depicts the relationships between different levels of systems integration and multiple building systems through major project stages, from project start to project close (Whyte and Davies 2021).

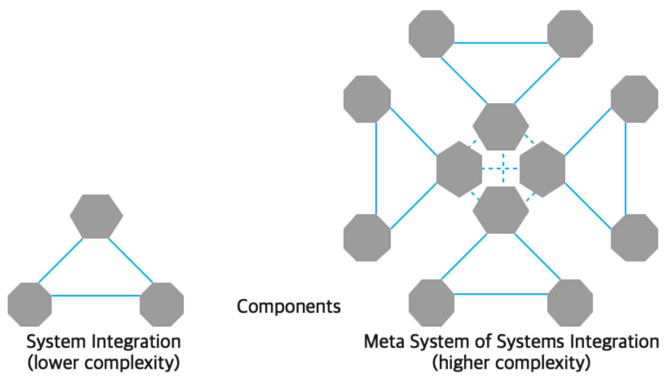


Figure 8. Levels of system integration (Davies and Mackenzie 2014).

At the lower level of project complexity, various components and subsystems are integrated into a system architecture to perform the required functions and satisfy the requirements of the operator or end-users.

At the higher level of project complexity, the system of systems (metasystems) joins with a large-scale array of platforms and systems to achieve common project goals.

Systems integration plays a crucial role in the success of productised construction projects, because it requires coordinating work across different levels of systems, such as components, subsystems, systems, system of systems, and operational systems. Zerjav et al. (2018) and

Muruganandan et al. (2022) identify an **integrator** as a key player in complex projects. An integrator is a **person or a company that specialises in integrating components or subsystems to ensure they function together**. The integrator defines the overall design, components, and interfaces between them in a project system. The integrator coordinates the network of component or subsystem suppliers involved in phases such as design, production, construction, commission, and handover to operations.

Figure 9 presents the adapted 'V' model of systems integration in construction projects. It depicts the relationship between different levels of systems integration, building systems, and interfaces during major project stages including project start, design, production/construction, test-built deliverables, and close (Whyte and Davies 2021).

In the **project start** stage, requirements of operators and end-users and project outcomes are considered to develop the first iteration of systems. This start stage usually contains planning for productisation before conceptual design.

The **conceptual** and **detailed design stages** (i.e. specifications and construction drawings) requires the integrator's understanding the components, subsystems, and interfaces designs to configure in the whole building system. The system integrator coordinates and controls the network of contractors and suppliers involved in the design of components, subsystems, systems of the system, and overall operations.

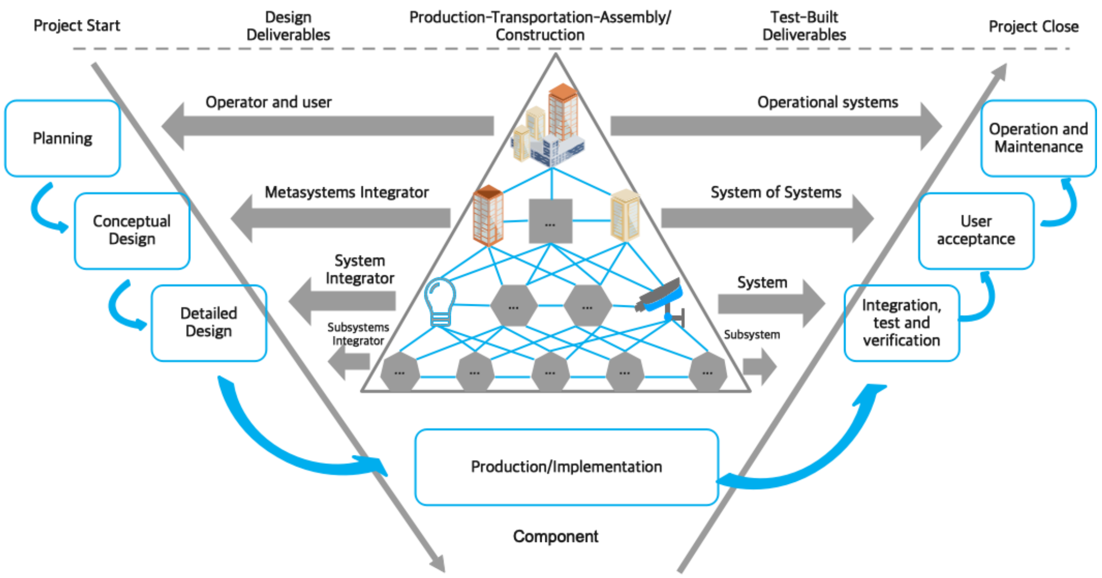


Figure 9. Lifecycle-based 'V' model of systems integration.

The **production–transportation–assembly/construction stage** is crucial for success. Producing components and subsystems at factories and transporting them to the construction site requires careful planning and execution. The assembly work then begins on site, with construction managers and subcontractors working together to complete the project on time and to the required quality standards.

For example, in the Brock Commons Residential project, using a mass timber structure and facade components produced at factories and concrete work on site allowed for a more efficient construction process. It required a flexible system integration approach to allow for evolving requirements and architectures to be incorporated in a controlled way during delivery. Subsystem integrators integrated components into subsystems, which were then integrated by system integrators. Finally, a metasystem integrator oversaw the configuration and integration of the system of systems.

In the **test-built deliverables stage (pre-construction),** prototypes and version-controlled configurations are tested and verified to explore design alternatives, test theories, and confirm performance and functions. This stage helps to ensure the final product meets the required standards and specifications.

In the **project close stage**, the fully operational system is completed, and the metasystem integrator works with the operator responsible for ongoing operations. This ensures the system is maintained and operated as intended, and any issues or problems are resolved in a timely and effective manner.

In complex construction projects, systems integration plays a crucial role in ensuring the smooth communication and management of electronic product and project data between diverse software and hardware systems (Shen et al., 2010). The success of this process depends on the seamless coordination of multiple stakeholders or specialists involved in different components, subsystems, or systems of systems with ‘clean interfaces throughout the project lifecycle. To optimise this process, current research explored various system integration approaches (Table 4).

Table 4. System integration approaches.

Researchers	System integration approaches	Levels
Shen et al. (2010)	Building information models (BIM) Distributed objects/components Software agents Integration of RFID and wireless sensor networks	Project
Whyte and Davies (2021)	Phase	Phase
	Specialist function Project-level technical process	Project
	Program-wide strategic function	Program
Ansar and Flyvbjerg (2022)	Platforms	Program/portfolio

In the realm of complex construction projects, systems integration emphasises the smooth management and communication of electronic product and project data among diverse software and hardware systems. Whyte and Davies (2021) proposed 4 approaches to systems integration: phase, specialist function, project-level technical process, and program-wide strategic function. Ansar and Flyvbjerg's (2022) and Shen et al.'s (2010) research further categorises systems integration approaches into phase, project, and program/portfolio levels. The project-based approach focuses on significant cyber-physical complexity and involves interconnecting physical and computational processes. Information technologies, such as BIM and RFID, enables centralised information integration. The project-level technical process manages technical coordination and changes at the component, subsystem, and system levels. The portfolio-based or program-based approach uses platforms for program management and end-user relationships. These approaches provide a framework for carefully considering systems integration strategies in decision making processes of project delivery models.

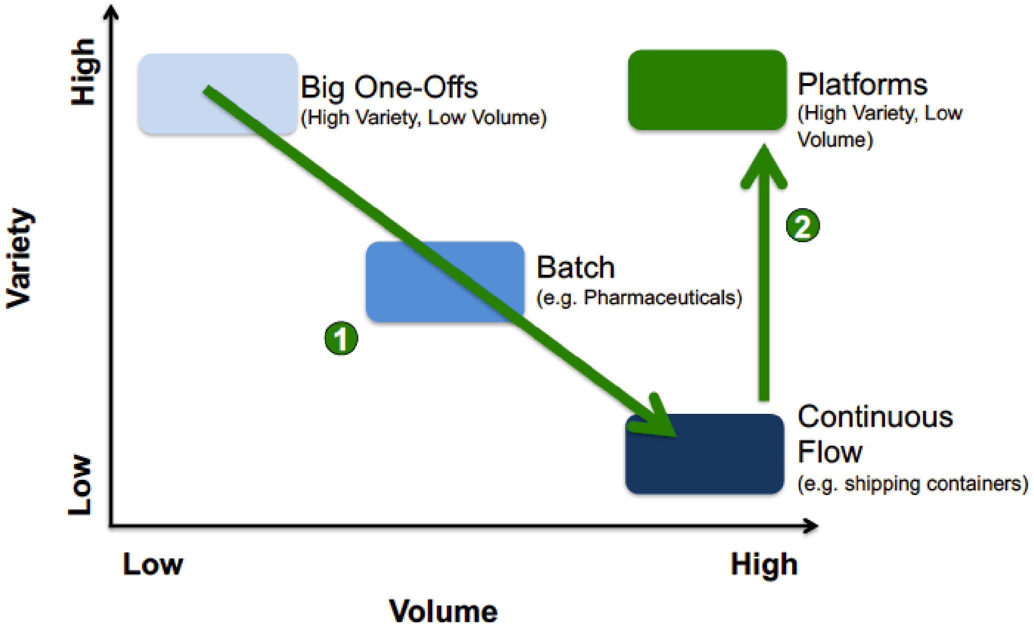


Figure 10. Volume/variety matrix (Ansar and Flyvbjerg 2022)

The advantage of repeatability in construction modules is its ability to increase homogenous volume and predictability (line 1), which allows for variety at scale by combining modules in different ways (line 2) (Figure 10). Platforms have the potential for exponential extendibility and absorptive capacity, meaning they can learn from the internal and external environment. As a result, platforms can be repurposed and upgraded to form complex construction systems. Information technology offers various platforms that can coordinate and integrate workflow and information throughout the project lifecycle.

6.8 Discussion

The study highlights the use of ICTs in different stages of productised building projects. Specifically, Cluster 1 focuses on using BIM in designing and analysing building systems (Figure 11).

The Brock Common project is presented as an example to demonstrate how BIM can be used in different stages of the project:

- During the design stage, BIM integrates design iterations and updates from different members of the design team into an as-planned digital model. This helps achieve horizontal integration of the building system and facilitates communication through big room meetings. Once the as-planned BIM model is completed, it can be used to produce detailed modular drawings of building components for the producer at the project level, as well as visually present the building system interference to contractors.
- During the production–transportation–assembly stage, the as-planned BIM model gives precise measurements of modular components to the producer, enabling perfect fitting of components in the building system and reducing physical interfaces. BIM model also analyses the exact data of the site, identifies the configuration through feedback of construction and production, and manages and controls configuration changes by updating and revising the as-planned BIM model to as-built BIM model. Configuration audits via inspections ensure the completeness and accuracy of the final as-built BIM model.

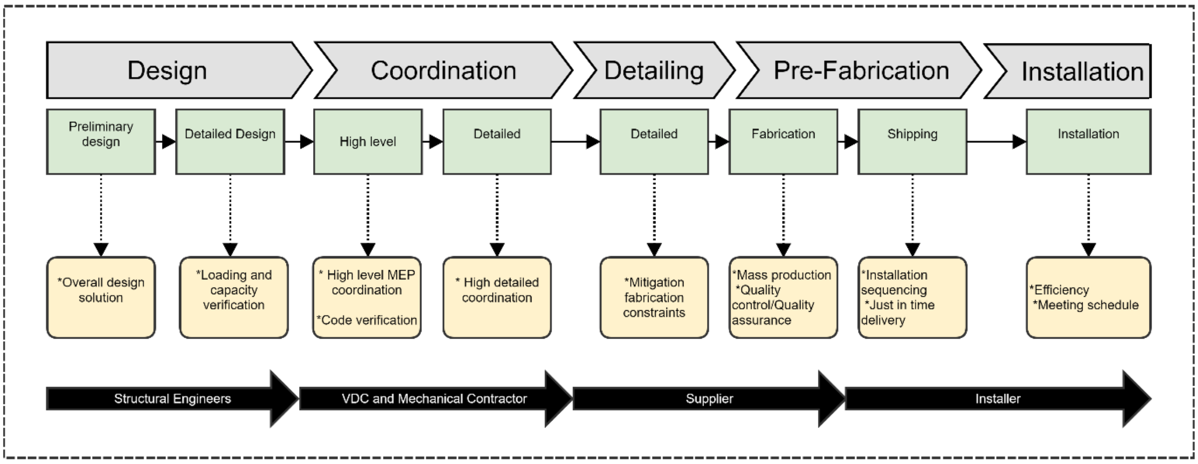


Figure 11. Hand off, constraints and responsibility (adopted from Fallahi et al. 2016).

Using BIM enhances coordination by simplifying interfaces and reducing interdependence for integrated or modular building systems. It also embeds configuration management in the process of as-planned, as-built, and final as-built models to effectively anticipate, manage, and execute changes. Overall, using ICTs streamlines the building lifecycle, provides a safer and more productive environment for end-users, and increases operational efficiency for owners.

However, a key element of BIM or other ICTs is interoperability between various software used in the design and construction process and a common data format for the efficient exchange of design information and knowledge. This should be emphasised in industrial development.

The second cluster of findings highlights the crucial role of interface management in the productised project lifecycle, which involves physical, contractual, and organisational interfaces. Effective interface management is essential for achieving horizontal, vertical, and longitudinal integration, which presents significant challenges across the project lifecycle. The mirroring hypothesis illustrates the extent to which an organisation or deliverable is modular or integral, which can support collaboration in productised projects. The quadrants in Figure 12 demonstrate the different levels of modularity and integration in deliverables and organisations, which can facilitate coordination and reduce interdependence.

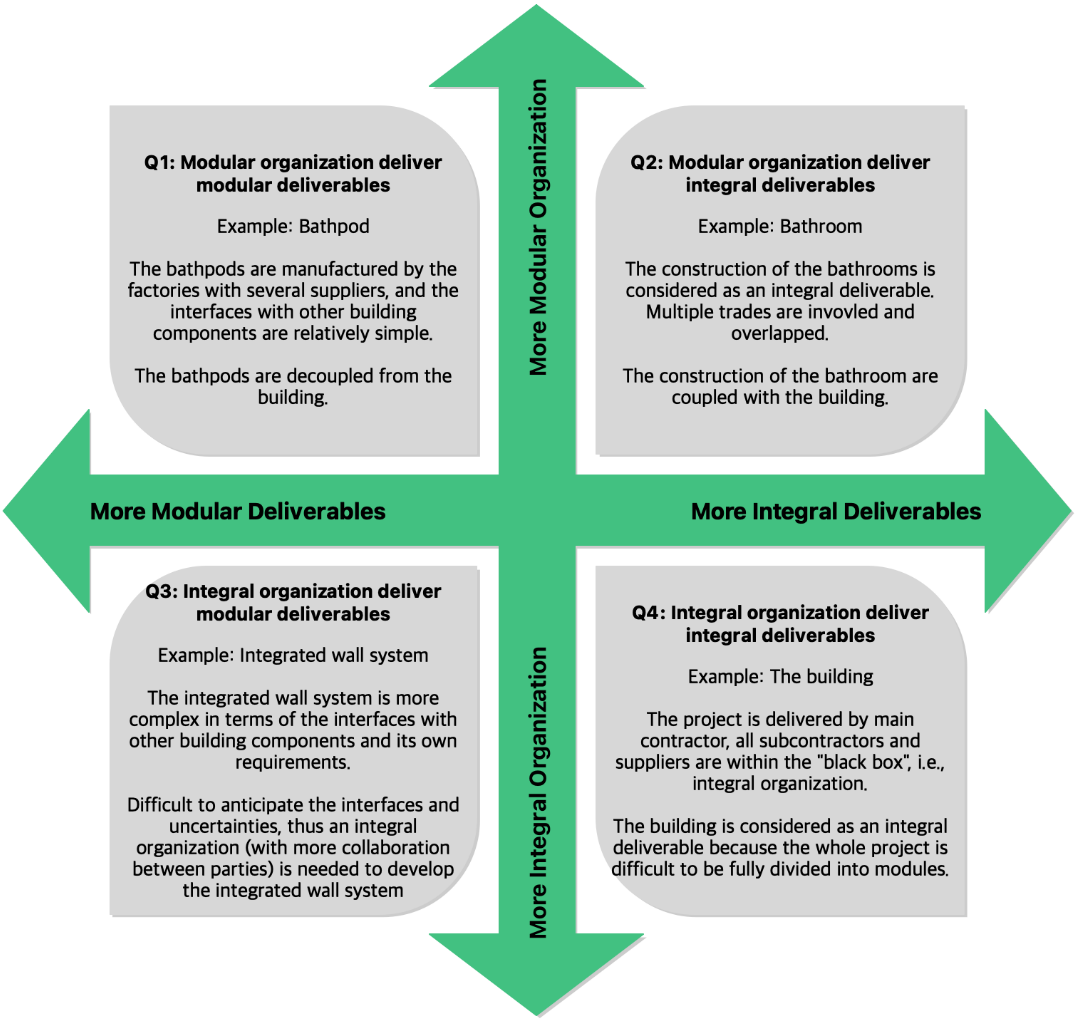


Figure 12. Organisational versus product modularity and integration.

Using standardised components, productisation, and interface compliance in modular designs can enhance coordination and reduce complexity and interdependence in large-scale building projects. In contrast, integral deliverables and organisations require a high level of cooperation and solutions to deal with interdependence challenges. Modular designs can also facilitate longitudinal integration by reducing the number of interdependencies across projects. Effective interface management during the design stage can minimise interface issues over the project lifecycle, thus reducing risk. Overall, interface management is crucial for achieving successful productised project outcomes.

In the productised project lifecycle, systems integrators play various roles. Table 5 presents the characteristics of systems integrators in building projects, highlighting their technological and coordination roles. Assembly projects typically involve a single organisation, often with the assistance of other functional groups, and a small team working in a single location. In contrast, system projects involve a main contractor responsible for delivering the product, with tasks divided among several subcontractors, both in-house and external. Array projects are coordinated by a central umbrella organisation, often a separate entity or company, and address financial, logistical, legal, and political issues. These projects are often spread over a wide geographical area and consist of several subprojects.

Table 5. Characteristics of system integrator role by level in building projects.

	Role	Aspects Integrated	Sources of Complexity	Tools/Routines	Core Capabilities	Stakeholders
Strategist System Integrator	• Integrating the institutional scope, the business model as well as the political agenda of the stakeholders	• Institutional scope, political agenda, business model	• Complexities related to market,competition, technology and fuzzy goals • A new technology that has not yet been used by other similar firms	• Market analysis and research to determine market trends (performed by consultants) • Routines developed to guide the Business Process Reengineering and change management process • Pilot projects to cope up with the complexity of new technologies • Specialized software systems,simulation • Economic and socio-political analysis.	• A high level of understanding of a corporation from a top management perspective • Managers,or consultants with high academic qualifications and/or high specialized expertise • Knowledge and creative ideas • A full understanding of market dynamics and needs	• The regulator which could be a state or a government who issues new standards and rules to which the firm should conform • Market analyst which provides valuable statistics and market research on the latest trends of technology • Unions or pressure groups such as environmental organizations which could play a major role when building a new nuclear power plant or a hydroelectric dam • Users and the ultimate clients who are affected directly by the new project
Architect or Designer System Integrator	• Mainly a technological role • Some sociopolitical activities are required • New technologies will need to be coordinated with current systems as well as the political agenda of the stakeholders	• Technological dominance, political agenda, business model	• The need to bridge the gap between the new solution and the current system/architecture (the dominant standard) • Changes to the current infrastructure or the introduction of a radical innovation • Other challenges such as security,quality and reliability requirements	• Technology and system knowledge • Feasibility studies,load analysis,specialized software systems • Pilot projects	• Technology and system knowledge • Staff with high–medium academic capabilities/ technical or engineering background • High–medium experience	• Vice president or a business unit leader who is responsible for the project • Program manager assigned to the project • External parties who interact in this phase besides the system integrator (architecture team): the product/solution provider and the experts • Pressure groups,entrepreneurs and users
Implementer or Project Manager System Integrator	• Coordination of different types of resources and tasks to implement the final solution – project management	• Resources,tasks	• Coordination,conflict resolution,risk mitigation and communication	• Various project management plans,project management information system and earned value techniques • Tools and routines could use other templates and follow standards such as ISO or Capability Maturity Model • Tracking software	• High level of project management skills in different knowledge areas	• A program project manager who represents the client and interacts with other stakeholders (could be the system integrator) • Project sponsors,auditors, quality department,the solution/ product provider,the project team,the project management office and a steering committee • Certification
Operator of Support System Integrator	• The solution and the client operations are supported • Integration of services and routines	• Services,routines	• Process optimization and service level are the main sources of complexity • The service level could decline with time,causing small problems to become high priority • The need to continuously improve the service level and response time	• Templates and forms, process diagrams and flow charts • Routines summarized in user guides, communication plans and escalation plans (in the case of a problem or an emergency)	• Low–medium academic capabilities and low–medium expertise • Some technical expertise is needed when the system integrator is responsible for upgrading and maintaining the solution or system	• Client,ultimate client • Functional leader • Product provider • Users

Digital technologies have enabled the creation of clear interfaces between subsystems and processes, increasing modularity. From the perspective of designers, architect or designer systems integrators possess core capabilities such as technology and system knowledge and high–medium working experience. They are involved in the design and plan phase, procurement phase, and execution/construction phase. During these phases, they establish strategic relationships with clients, coordinate with contractors, project management firms, and various consultancies, and manage conflicts and risks. On the other hand, implementer or project manager systems integrators are responsible for coordinating different types of resources and tasks to implement the final solutions. Effective collaboration among different systems integrators within a project is crucial for achieving project targets.

6.9 Findings and recommendations

A systematic analysis of productised project delivery from a lifecycle perspective is crucial in obtaining insights into best delivery practices and opportunities for continuous improvement. Figure 13, adapted from Wuni, Shen, and Darko (2021), outlines the key considerations, relevant stakeholders, and deliverables for each lifecycle stage. Figure 13 highlights the best practices, typical deliverables, and best practice indicators for each stage, further elaborated in Chapter 7. The lifecycle framework emphasises the importance of early commitment and ‘starting right’ as early phases strongly influence the success of later phases. Allocating best practices and indicators to different lifecycle stages provides practical understanding and insights into management and performance evaluation. Moreover, the framework can help project teams evaluate performance in each phase and take timely corrective actions. Comparing this framework to current practices can provide organisations with a clear picture of gaps and areas for improvement when implementing productisation.

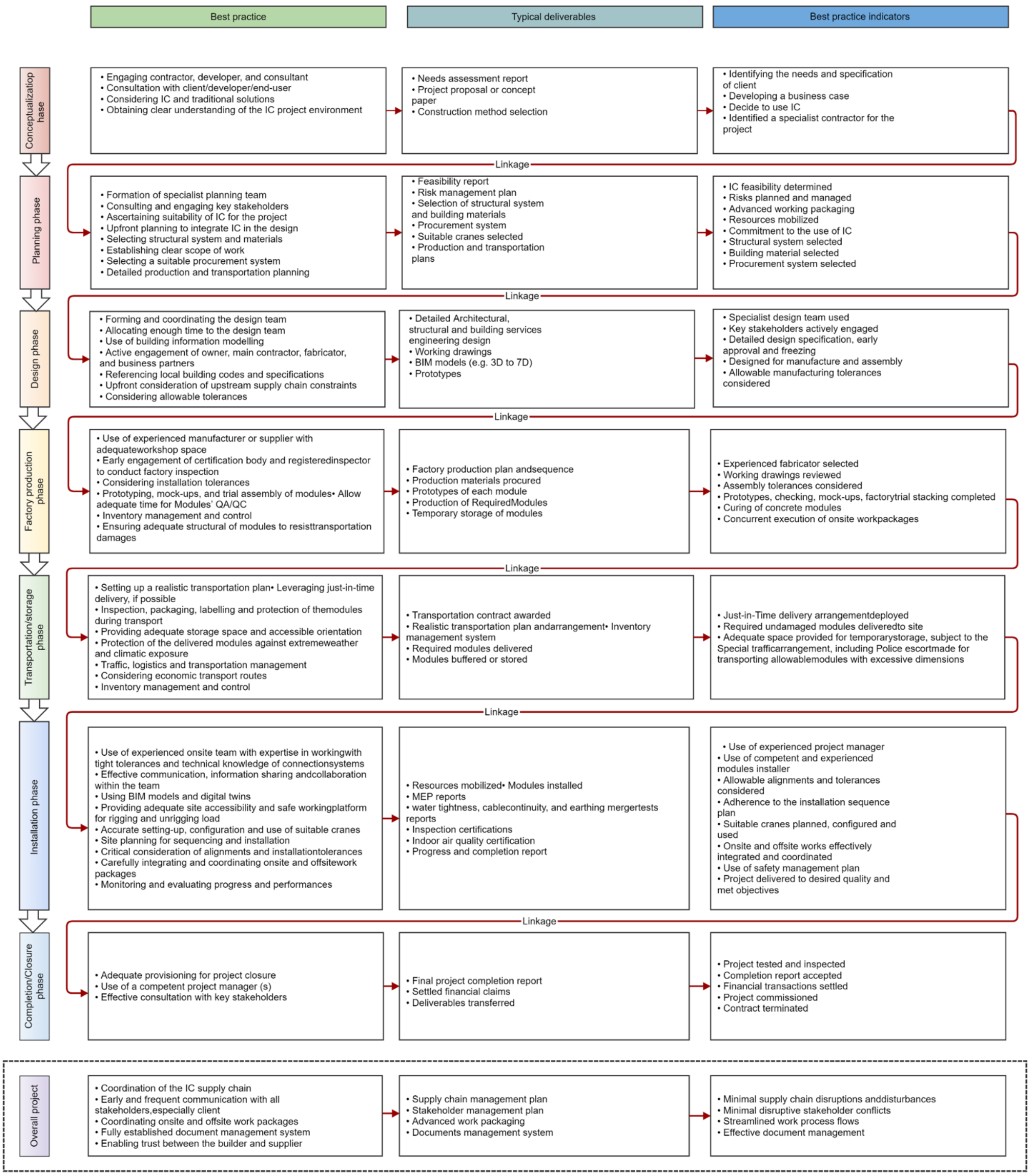


Figure 13. Typical deliverable, and best practices indicators for each phase. Adopted from (Wuni, Shen, and Darko 2021).

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Appendix A. [1] Systematic literature review summary

The relevant literature was identified with keywords, i.e., TITLE-ABS-KEY was set as (‘systems integration’ OR ‘interface management’) AND (‘construction’ OR ‘building’). Searching was conducted in Scopus limited to publications in English that were published since 2010. A total of 30 papers were filtered for a systematic review of definitions, theoretical foundations, approaches, and a visualised keywords co-occurrence analysis.

Figure 20 displays a co-occurrence network resulting from VOSviewer analysis. The network consists of 25 keywords and their links, representing their co-occurrence in at least one publication. The size of each node reflects the frequency of occurrence of the corresponding keyword, reflecting the key concept of knowledge cluster of systems integration research. The larger the node, the more frequently the keyword appears.

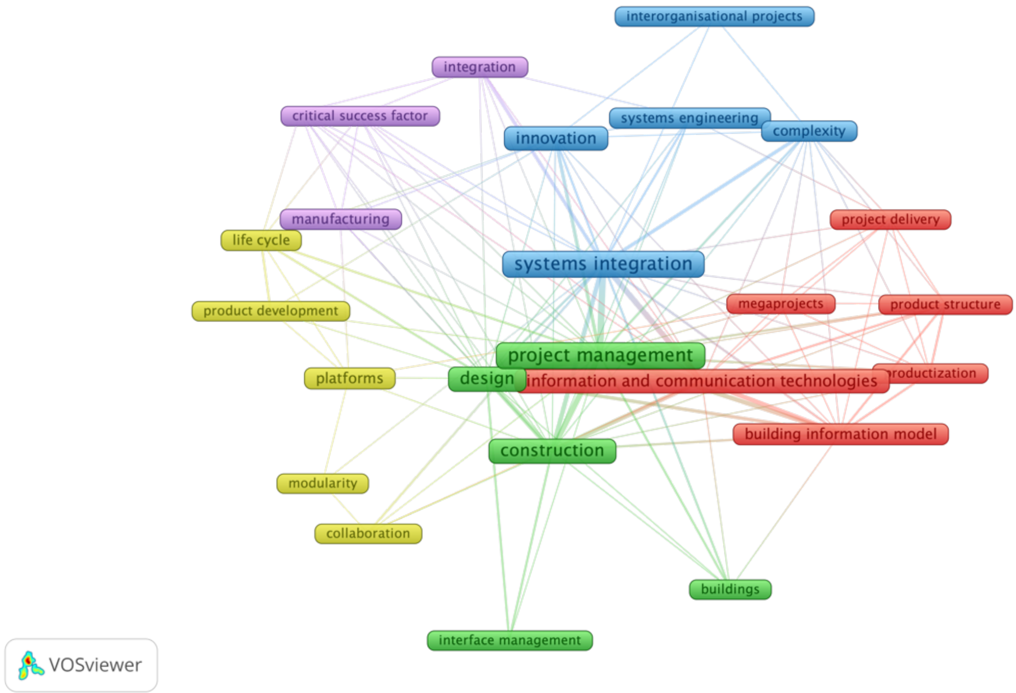

Figure 14. Keywords co-occurrence network.

Cluster 1: BIM and information communication technologies (ICTs)

Cluster 1 focuses on BIM and ICTs in construction projects, particularly megaprojects, to enhance project delivery and improve productivity and quality. BIM enables virtual construction and consistent handling of data for systems integration, while ICTs connect information and people across the infrastructure lifecycle. The key challenge is maintaining an integrated repository of information throughout the project lifecycle, requiring collaboration among project participants and alignment between design, production, and construction processes. Future research should prioritise developing a generic BIM-based platform for practical applications in productised construction, with guidelines and practical instructions for implementation.

Cluster 2: Design and interface management (IM)

This cluster comprises key concepts of ‘IM’, ‘building’, ‘design’, ‘construction’, and ‘project management’. Systems integration relies on effective IM to fit many interdependent components together and achieve the desired output (Muruganandan et al. 2022). Efficient IM is crucial for successful stakeholder management, communication, and deliverables (Shokri et al. 2016). Several approaches – such as an implementation guarantee system, IM-BIM integration, and IM practices like checklist preparation and PMIS application – have been proposed to resolve interface issues in large-scale construction projects (Shan and Zhang 2012; Eray et al. 2017; Ahn 2013). IM is also necessary in construction to ensure the components and systems of an integrated building can function well together (NSW Transport Asset Standards Authority 2018).

Cluster 3: Interorganisational projects and innovation

This cluster encompasses ‘complexity’, ‘innovation’, ‘interorganisational projects’, and ‘systems engineering’. Productised construction projects are interorganisational projects, where multiple organisations collaborate on complex products or services. These projects manage complexity by breaking them down into subsystems with well-defined interfaces and buffers. Systems integration is a critical challenge in the design and delivery of complex interorganisational projects, and innovation is expected via systems integration. Systems integrators in construction enable interorganisational innovation by coordinating and implementing innovations based on recombining and replicating a system or production processes.

Cluster 4: Collaboration and modularity

This cluster pertains to the concepts of ‘modularity’, ‘platforms’, ‘collaboration’, ‘lifecycle’, and ‘product development’. BIM and ICT advancements are supporting systems integration and collaboration technologies that facilitate the creation, management, dissemination, and use of information throughout the entire product and project lifecycle, integrating people, processes, systems, and information more effectively (Shen et al. 2010). The ‘V’ model demonstrates the systems integration and collaboration required throughout the project lifecycle. Modularity is necessary to ensure productivity and optimal product family design, because it allows for the generation of product platforms and modules, and identifies components for potential integration (Agrawal et al. 2013). Modularity and integration are complementary, stimulating collaboration (Tee et al. 2019).

Cluster 5: Critical success factors (CSFs) and manufacturing

This cluster encompasses the key concepts of ‘CSFs’, ‘manufacturing’, and ‘integration’. Manufacturing (often seen in productised construction, prefabricated construction, and off-site construction) is a group of digitally controlled additive processes that has the potential to impact construction processes (Buswell et al. 2008). To meet industry 4.0 requirements, which involve widespread application of automation technologies and the adoption of lean construction, systems integration can be used as a mature concept in manufacturing (Doh et al. 2016). Critical factors such as interoperability, legacy systems, and human-system interaction must also be examined to improve systems integration performance (Madni and Sievers 2014).

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