

Roadmap for Automated Compliance Checking Adoption in New Zealand Offsite Manufacturing Industry

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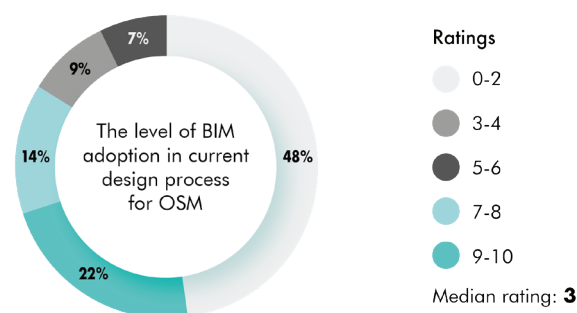
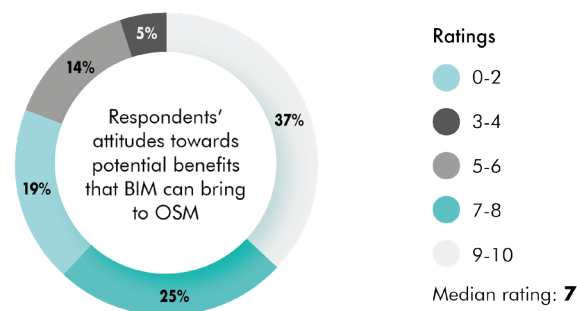
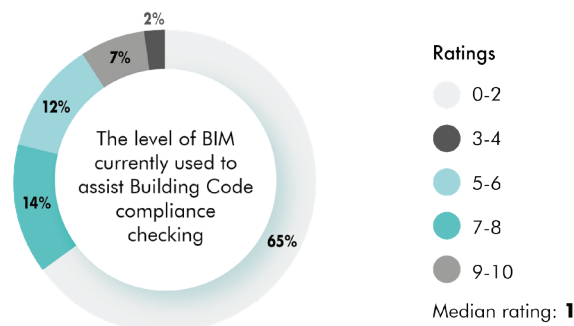
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Executive Summary

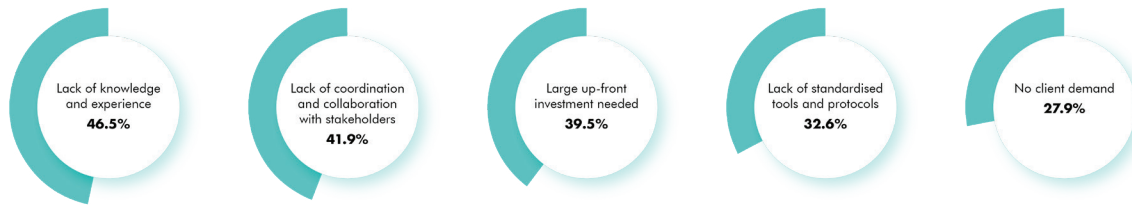
New Zealand (NZ) demand for efficient Offsite Manufacturing (OSM) solutions to meet the shortfall in affordable housing is high. OSM, where building components are assembled in a factory and transported to construction sites, can significantly improve productivity and speed-up project delivery. However, NZ's labour-intensive, time-consuming, and error-prone manual compliance-checking processes are causing bottlenecks, preventing the speedy delivery of OSM projects.

Automated Compliance Checking (ACC) is a process using software to assess building designs against compliance requirements without modifying the designs, and has great potential to improve productivity and expedite delivery of OSM projects. In recent years, the industry has seen the emergence of novel ACC approaches and the start of promising commercial implementations. However, the OSM industry is generally not familiar with ACC processes and little is known as to how well the ACC technology can serve the OSM industry.

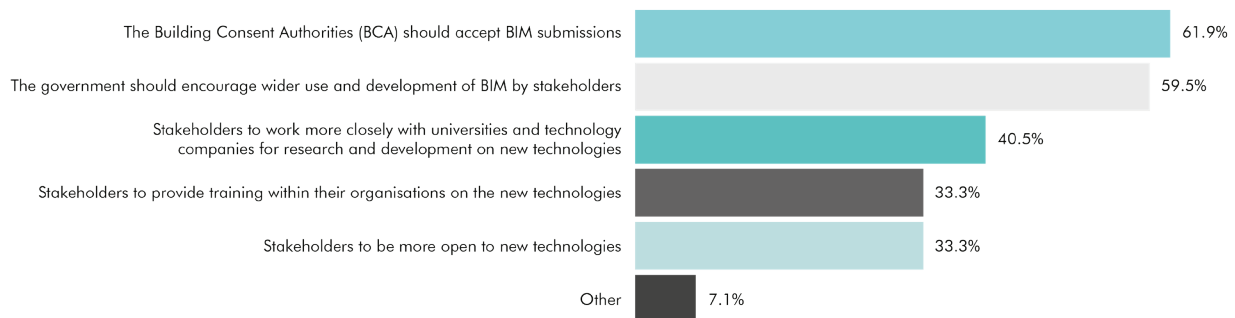
The two-part study, investigating the NZ OSM Industry's Readiness for ACC, surveyed 44 industry stakeholders to understand how they are using Building Information Modelling (BIM), their awareness of the potentials of ACC, and what actions can boost their adoption of ACC technology. Key results of the survey are outlined as below.



The most critical barriers to low BIM implementation:



Critical barriers to ACC technology adoption



The study then interviewed 16 international ACC experts, and conducted a focus group with nine local OSM stakeholders to develop a high-level roadmap to facilitate wider ACC adoption in the NZ OSM industry. The roadmap identified three action areas - technology, organisation, environment - where changes can be made to support the NZ OSM industry in adapting to ACC. Actions to help the industry develop technology include;

- Developing a BIM modelling and information standard for OSM projects
- Improving standardisation in using terminologies and describing OSM building Systems
- Government and BCA leading the development and endorsement of a computer-processable version of NZBC
- Technology firms consistently improving the maturity of ACC technology
- Technology firms and researchers co-developing methods for checking the quality of BIM - and semantically enriching it to improve visibility
- BCA and technology firms co-developing a standard method of interpreting NZBC and improving its coverage
- Using a third-party to conduct quality assurance of digital NZBC, the maintenance of which should be led by Government/BCA
- BCAs developing an ACC conflict solution framework
- BCAs and OSM industry leading the development of a BIM models repository
- OSM industry and BCAs developing tested recommendations on suitable tools via a publicly available library
- Technology integration led by technology firms.

Actions to support organisations within the industry – including tertiary institutions, government, and OSM industry businesses - include;

- Improving education and training to facilitate wider BIM use
- Government support to improve BIM adoption in SMEs
- Skill improvements for BCA officers in checking BIM models with other digital data for building consent assessment
- Technology firms having early stakeholder engagement to understand the real needs and challenges
- OSM industry leading the establishment of an industry panel or advisory group to support ACC development, testing and adoption
- Technology firms provide appropriate, trust-building marketing of ACC technology that doesn't oversell or promise underdeveloped functions
- OSM industry and BCAs conducting pilot projects and case studies to test the ACC technology in real OSM projects in NZ
- BCA officers improve their skills in using ACC systems for building consent assessment.

Actions for BCAs and Government to improve the overall industry environment in using BIM and ACC include;

- Government developing national strategy to promote BIM in OSM industry
- BCAs accepting BIM submissions and creating guidelines for BIM-based OSM building consent assessment and ACC
- BCAs developing a national checking procedure standard, and updating ACC-based building consent procedures
- Government providing upfront investment to support ACC research, testing, foundation establishment, and adoption
- BCAs providing incentives to encourage e-submissions for ACC.

1.Introduction

Offsite manufacturing (OSM) refers to the construction method of assembling building components in a factory and transporting them to the construction site for final installation (Goodier and Gibb 2007). Compared with traditional construction, OSM can significantly improve productivity and speed up project delivery through achieving a higher level of resource utilisation and allowing the offsite production and onsite construction works to be conducted concurrently (Boyd et al. 2013; Hanna et al. 2017; Ko and Wang 2010; Panjehpour and Ali 2013; Tam et al. 2007). OSM has been recognised as a promising solution to the shortfall of affordable housing demand globally (Thompson 2019). With the rapid development of advanced information technology (ICT) in recent years, numerous efforts have begun employing Building Information Modelling (BIM), which refers to the collaborative process of creating, sharing and utilising information of the building lifecycle (Eastman et al. 2011), in OSM projects. The integration of BIM and OSM brings benefits such as improving information exchange and modelling (Nawari 2012), addressing schedule delay problems (Li et al. 2017), and managing production flows (Arashpour et al. 2018).

In response to the increasing housing demand in New Zealand (NZ), the Ministry of Business, Innovation and Employment (MBIE) has set policies and plans to prioritise the development and use of OSM (MBIE 2018). However, the benefits of speedy delivery of OSM projects cannot be fully realised due to current bottlenecks with the manual compliance checking processes, which are labour-intensive, time-consuming, and error-prone (Dimyadi and Amor 2013). Furthermore, unlike conventional processes, OSM requires the preapproval of various functional components before the final installation. The performance-based NZ regulatory framework can support the unique compliance requirements of OSM. The NZ Building Code (NZBC) enables innovative design, engineering, and construction processes to be explored and implemented without the need to follow rigid and often overly conservative prescriptive rules (Dimyadi et al. 2020). However, the performance-based design presents its own challenges due to the iterative peer-review process that can take weeks to months to complete, particularly if there are differences of opinion among peer-reviewers, which may add uncertainties to project delivery timing. Undesired iteration cycles can be a major cause of project delays and cost increases in construction planning (Preidel and Borrmann 2016). Additionally, OSM is a non-linear construction process that shifts complex compliant design and construction tasks to the early stages, thus preventing design changes downstream. It also involves early site preparation so that modular components can be stored on site, the simultaneous running of various logistics, and both offsite and onsite work (PrefabNZ 2018a). Consequently, OSM needs to not only meet the performance outcomes of the NZBC, but also satisfy a wider range of requirements, including those in the Manufactured Modular Component Guidance in New Zealand (Auckland Council 2020) and the Handbook for the Design of Modular Structures in Australia (James et al. 2017).

BIM enables Automated Compliance Checking (ACC) of building designs (Choi and Kim 2008) by sharing machine-readable building data to support automated compliance decisions (Martins and Monteiro 2013). To date, most modern ACC approaches rely on BIM as the essential data input to supply geometric and semantic information with adequate level of details (Costin et al. 2018). A common methodology is to convert proprietary BIM models into the international BIM standard (Sadrinooshabadi et al. 2020) format, namely, Industry Foundation Class (IFC), and then to check this model using pre-defined rules (Malsane et al. 2015). According to Eastman et al. (2009), modern ACC approaches often follow a four-stage process, namely (1) rule interpretation, translation and logic structuring; (2) building model preparation with the required level of details; (3) rule execution and checking; and (4) reporting of the results. In recent years, the industry has seen the emergence of novel ACC approaches and the start of promising commercial implementations.

Integrating ACC into OSM workflows has the potential to improve productivity and expedite project delivery. However, the OSM industry is generally not familiar with ACC processes, and little is known about how well ACC technology can serve the OSM industry. As OSM has a unique set of workflows that is different from traditional construction methods, there may be challenges in adopting ACC technologies in OSM projects. Specifically, this study addresses the following research questions (RQs):

- **RQ1.** What is the current status of BIM adoption in the NZ OSM industry?
- **RQ2.** To what extent are OSM stakeholders aware of the potential of ACC?
- **RQ3.** What actions can boost the adoption of ACC technology in the NZ OSM industry?

The rest of this report is organised as follows: The next chapter reviews literature on the integration of OSM and BIM, regulatory compliance processes, and the general adoption of ACC technologies. This is followed by the overall research design and methods, which are then followed by the results. The final two chapters present discussion and conclusions of the research findings.

2. Literature Review

To provide a context for the research reported in this report and to support the design of the survey questionnaire, this section briefly reviews relevant literature from the following three aspects: (1) OSM and BIM, (2) the current regulatory compliance checking process, and (3) adoption of ACC technologies.

2.1. OSM and BIM

Due to an increased demand for the speedy delivery of new buildings, OSM has experienced steady growth in NZ since the 2000s. According to PrefabNZ (2018a) and Kennerley (2019), there are five types of OSM in NZ, namely (1) components, (2) panels, (3) volume, (4) hybrid, and (5) complete buildings. Components and panels are 2D prefabricated units that do not enclose usable spaces (Bertram 2019). Components are small-scale items assembled offsite such as structural components. Panels refer to planar units that include windows, doors and integrated services. Volume, hybrid and complete buildings are 3D prefabricated units that enclose usable spaces, such as building modules, pods and complete building units, which are typically fully finished internally and can be directly installed onsite (Kennerley 2019; PrefabNZ 2018a).

Although the application of different OSM types is not limited to any specific building types, it was found that components and panels are best suitable for residential construction, modular prefabrication is ideal for highly serviced areas, and complete buildings are most suited for portable or temporary applications (Shahzad et al. 2014). BIM aligns with the core “integration” concept of OSM, which enhances the design processes through an early-stage decision making, detail optimisation, clash detection, better coordination and effective communication (Bonenberg et al. 2018; Ramaji and Memari 2015; Samarasinghe et al. 2015; Sharma et al. 2017; Singh et al. 2015; Solnosky et al. 2014), facilitates seamless and timely information exchange between designers and manufacturers, minimises design errors and discrepancies between the design and final products, and enhances mass customisation (Mostafa et al. 2020; Singh et al. 2015).

2.2. The current regulatory compliance checking process

The performance standard of all NZ buildings is legislated by a three-tier building control framework, i.e. Building Act, Building Regulations, and Building Code (MBIE 2014). As part of Building Regulations, the NZBC specifies the detailed provisions that all building works must comply with. Typically, all construction projects in NZ are required to comply with regulations from eight sections or technical clauses of the NZBC, which are (1) general provisions, (2) stability, (3) protection from fire, (4) access, (5) moisture, (6) safety for users, (7) services and facilities, and (8) energy efficiency (MBIE 2014). The NZBC is a performance-based code and sets out the functional and performance objectives that every building must achieve. Each technical clause in the NZBC is accompanied by a set of prescriptive compliance documents known as the Acceptable Solutions (AS) and Verification Methods (VM), which represent industry best practice minimum requirements and compliance solutions for a range of scenarios. Satisfying the full extent of any AS or VM is deemed to comply with relevant performance objectives of the NZBC. Given the performance-based nature of the NZBC, building designers can decide to propose innovative alternative solutions, subject to formal justifications, a peer-review process, and sometimes judicial rulings.

A building consent is typically required before any physical construction works can commence (PrefabNZ 2018a). It is a formal approval issued by the Building Consent Authority (BCA) confirming that the proposed design and construction solution complies with the building code and relevant normative standards. Evidence of compliance is generally provided in the form of design drawings, calculations, and supporting documentation. For building projects involving OSM, both offsite and onsite works must be included in the building consent application. In addition to overall mandatory compliance with the NZBC, OSM projects also need to demonstrate componentry compliance that must align with the project execution, which adds another level of complexity for compliance

checking. Particularly, there is a need to manage the iterative process of specifying building component details by integrating information from suppliers, contractors, and sub-contractors at different stages of the process (Gbadamosi et al. 2020).

Tolerance of parts should be carefully considered in the design for manufacture and assembly (DFMA) process, where standardised tolerance values learned from previous projects can be used as references to check the buildability for similar construction scenarios in new OSM projects (Shahtaheri et al. 2017). As suggested by Manufactured Modular Component Guidance in NZ, internal fixtures and fittings (e.g. toilet, shower, cabinets and doors, bed, wardrobe, desk) should be fastened to avoid any potential damage during transit (Auckland Council 2020). Such information should ideally be proposed and checked in the design drawings or models and inspected at the site of manufacture. The Handbook for the Design of Modular Structures (James et al. 2017), a guide for OSM and DFMA in Australia, specifies both regulatory and non-regulatory compliance requirements in the aspects of structure, building services, fire, acoustics, sustainability, facades, architecture, materials and manufacture, durability, safety, transportation, erection, temporary works, inspection, verification, disassembly, and recyclability.

Conventional approaches to demonstrating building code compliance in construction projects rely much on manual undertakings (Eastman et al. 2009; Malsane et al. 2015; Nawari 2019; Nguyen and Kim 2011; Preidel and Borrmann 2016; Tan et al. 2010; Zhong et al. 2012). Normative (legislative, regulatory, contractual) provisions are all conventionally conveyed in natural language subject to human interpretation. The inevitable variations in the interpretation of normative provisions between different people are a common problem. Although the official interpretation of the NZBC in the form of handbook is available, there are still grey areas that may arise from time to time depending on the project. This has posed a challenge, particularly when different experts from different disciplines use inconsistent or non-standard terminologies when assessing compliance of a given design (Ilal and Günaydin 2017). The undesirable iteration cycle of modifications among different evaluators can be a significant factor for project delays and cost escalation in construction planning (Preidel and Borrmann 2016). Moreover, the manual compliance checking practice usually demands face-to-face meetings, which can be considered inefficient due to the overwhelmingly huge volume of project information and design criteria to discuss and negotiate (Nguyen and Kim 2011). The process requires designers and evaluators to have a reasonably high level of skills as well as familiarity with the relevant regulations (Tan et al. 2010; Zhong et al. 2012). In the later stages of the construction projects, errors in building code compliance checking can potentially cause design changes that induce high and long-term costs of rework (Nguyen and Kim 2011), and sometimes even loss of life.

2.3. Adoption of ACC technologies

Some of the earlier ACC implementations include CORENET's e-PlanCheck in Singapore, the Solibri Model Checker (SMC) in Europe, SMARTcodes in the US, and DesignCheck in Australia (Ding et al. 2006; Khemlani 2005; Nawari 2011; Solibri 2020). However, most have not served the industry as intended, and some have not stood the test of time. For example, the CORENET e-PlanCheck was considered relatively successful at the time since government agencies as well as industry stakeholders were involved in achieving digitalisation of building plan submission, and checking and approval processes (Goh 2007). Unfortunately, it has not been fully utilised for various reasons. DesignCheck aimed in the early 2000s to automate the compliance checking process with the Australian accessibility building code, but it was not taken up by the industry, and no further development has been undertaken.

In recent years, the construction industry has seen the emergence of novel ACC approaches and the start of promising commercial implementations. The timeline of the development of various ACC approaches over the last half of the century has been summarised by Dimyadi and Amor (2013). These ACC approaches follow different technical routes; for example, language-based rule interpretation (Dimyadi and Amor 2017; Dimyadi et al. 2017; Lee et al. 2016; Lee et al. 2015; Park et al. 2016; Preidel and Borrmann 2015; Preidel and Borrmann 2016; Preidel and Borrmann 2017; Solihin and Eastman 2016), linked-data and semantic technology (Beach et al. 2015; Bouzidi et al. 2012; Bus et al. 2018; Dimyadi et al. 2016; Jiang et al. 2019; Lu et al. 2015; Yurchyshyna et al. 2007; Zhong et al. 2012), rule engines (Beach et al. 2013; Kasim et al. 2013; Lu et al. 2015), and natural language processing

(Zhang and El-Gohary 2014; Zhang and El-Gohary 2017; Zhang and El-Gohary 2019). Additionally, although most ACC approaches heavily rely on BIM data as input (Costin et al. 2018), a number of construction projects, especially in developing countries, still use 2D drawings. There have been efforts to try to extract essential information from 2D drawings and establish 3D semantic understanding of construction projects (Elyan et al. 2020; Zhao et al. 2021), which can then support ACC purpose (Wang et al. 2021), e.g. an artificial intelligence-based ACC system for 2D drawings by Vanyi Technology Ltd (2021). In NZ, a novel human-guided automation employing a workflow-driven approach, known as the ACABIM approach, has recently been implemented commercially. ACABIM was used successfully in a pilot project on BIM-enabled consenting by a BCA (Amor and Dimyadi 2021).

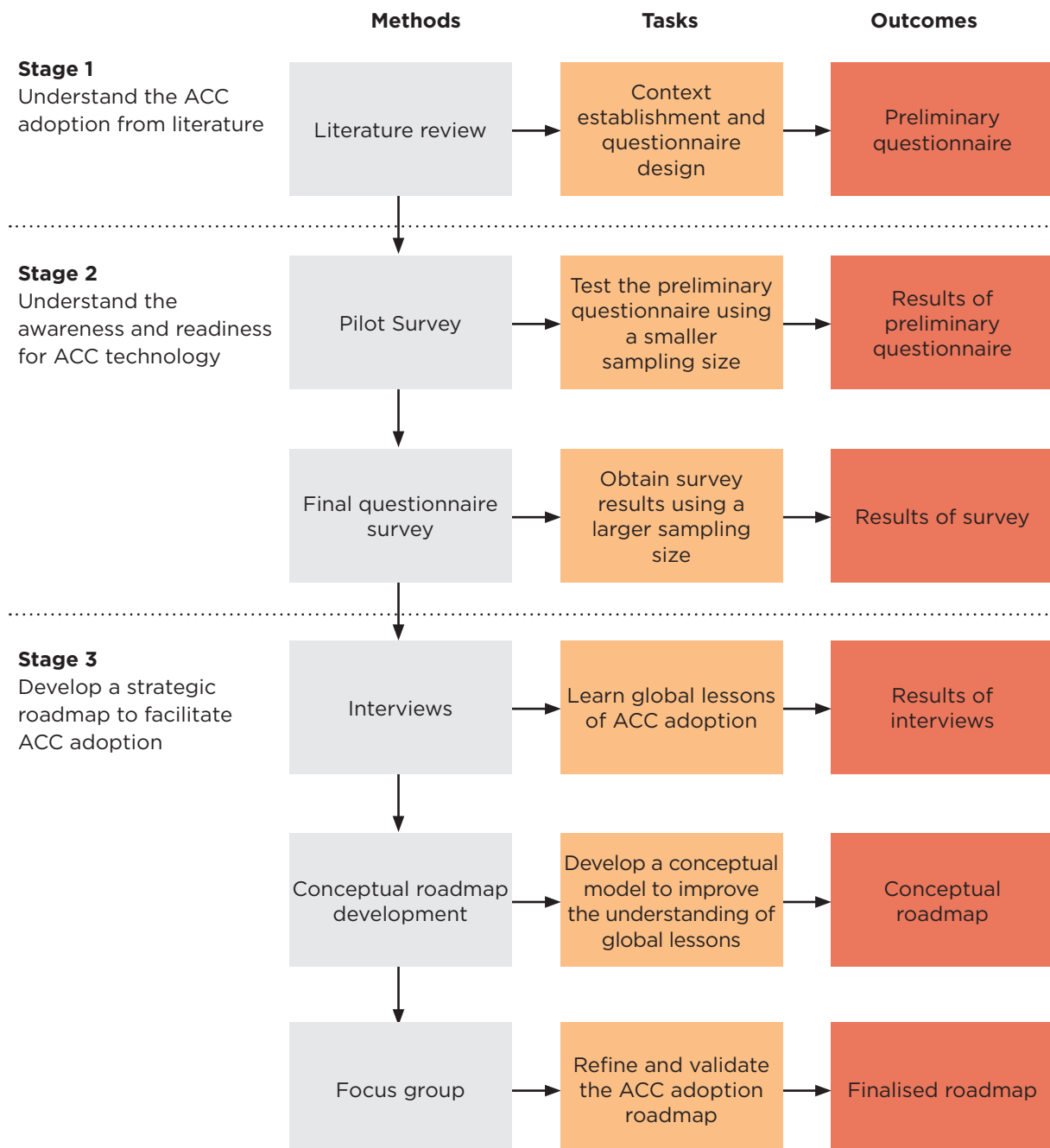
Currently, ACC is usually the task of designers and BCAs. ACC brings direct benefits to designers and BCAs through checking design solutions against regulatory requirements and suggesting any identifiable inconsistencies and non-compliance (Lee 2021). This is further facilitated by a global transition from paper-based documents to digital data (e.g. CAD drawings, BIMs, digital documents) for checking and approving designs online. For example, the Korean government has funded the development of a BIM-based e-submission system to support their national building permitting processes (Kim et al. 2020). Local governments in China have been collaborating with technology firms to develop and use online systems for checking building designs against building codes (Wang et al. 2021). Similar attempts have been reported in Norway and Singapore (Hjelseth 2015). ACC has applications in all stages of a project lifecycle, e.g. automatic identification of fall hazards through checking BIM against the rules from Occupational Safety and Health Administration (OSHA) (Zhang et al. 2013), and checking of construction operation plans (Salama Dareen and El-Gohary Nora 2013).

To date, ACC systems have not been broadly used in the construction industry (Beach et al. 2020). Although previous studies (Amor and Dimyadi 2021; Dimyadi and Amor 2013; Eastman et al. 2009; Hjelseth 2015; Krijnen and Van Berlo 2016) reviewed ACC software development and implementation, they were all technology-focused and did not provided insights into other non-technological challenges. For example, Amor and Dimyadi (2021) summarised that ACC development has focused on “addressing challenges in sharing digital architectural and engineering design information, formalising normative provisions as computable rules, and methods of processing them for compliance”. Despite the developments in technology, the literature (Lee et al. 2003; Tornatzky et al. 1990) has revealed that factors such as human perception and policies significantly contribute to the successful adoption of any new technology. A recent survey study by Beach et al. (2020) ascertained a set of obstacles that prevented the wide adoption of ACC in the whole built environment and proposed a vision for future ACC development and implementation. However, this research focused on the wider built environment in the UK context and was limited by only surveying industry professionals who might not be familiar with ACC. This report aims to narrow that gap that no existing studies measured the NZ OSM industry’s readiness for ACC, learned lessons from global efforts on ACC adoption, and explained a strategic roadmap towards wider ACC adoption for NZ OSM industry.

3. Research Design and Methods

Given the abstract nature of the research topic, this study adopted a qualitative approach (Creswell 2009) and collected data through literature review, expert interviews, questionnaire surveys and focus groups. The research was carried out in three main stages, as presented in Figure 1.

Figure 1. The research process flow



3.1. Stage 1: Understanding ACC adoption from literature

In the first stage, a comprehensive literature review of ACC technology was conducted, and its results were used to design a preliminary version of the questionnaire. The questionnaire was semi-structured and consisted of a total of 22 questions in four sections. Section 1 aimed to collect the participants' personal information regarding their specialisation and experience with OSM projects. Section 2 was about the NZBC and existing compliance checking processes. The shortcomings in the current practice of building code compliance were explored through questions about the most challenging sections of the NZBC, and the specific tasks or aspects of the building code compliance process that need to be improved. The participants were then invited to provide a number of problems that they believed could be resolved by ACC technology. In this section, the participants were also asked to provide an estimate of their time and effort spent on the manual building code compliance processes, and any alternative (semi-)automated solutions they are currently using. Section 3 was designed to answer RQ1, which investigates the current state of the BIM uptake in the NZ OSM industry as BIM is highly relevant and essential for modern ACC approaches. The participants were asked to rate the use of BIM in their design processes, the significance of the benefits brought by BIM, how much they use BIM in code compliance checking, and the most critical barriers to the use of BIM in OSM projects. Section 4 aimed to answer RQ2 through investigating the participants' perception of integrating ACC into their existing practices and collecting their suggested actions to promote the adoption of the ACC technology for OSM projects. They were asked whether they saw a need to automate the process and whether they thought that the automated compliance with the NZBC could benefit OSM projects, their business, and the whole NZ OSM industry. This section also asked the participants what key stakeholders and governments should do in order to promote the adoption of ACC technology for OSM projects.

The questionnaire was designed for industry professionals with experience in defining compliance requirements, designing OSM products in accordance with regulatory building codes and non-regulatory requirements, or assessing OSM projects against compliance requirements. Since not all respondents were expected to have the knowledge and experience in all three areas (BIM, ACC, and OSM), most of the key survey questions were set as optional to ensure that the respondents could provide input to those questions which they had the confidence to answer constructively. Selectable options were summarised from the comprehensive literature review. For example, the selectable options for the question "What type(s) of OSM are included in your company's business scope?" in Section 1 were supported by Capacity and Capability Report of PrefabNZ (2018b). The selective options for the question "What do you think are the most critical barriers that limit your adoption of BIM in OSM projects?" in Section 3 were summarised from (Ahmed 2018; BIM Acceleration Committee (BAC) 2019a; BIM Acceleration Committee (BAC) 2019b; Ghaffarianhoseini et al. 2017; Pezeshki and Ivani 2018; Sun et al. 2017; Vass and Gustavsson 2017). Most questions also provided the option of "other" to allow respondents to express their own views through additional comments, thus improving the quality of the survey results. In particular, before the respondents were invited to answer the questions in terms of ACC, a visual workflow was added into the survey to assist their understanding on how ACC technology works.

3.2. Stage 2: Understanding the awareness and readiness for ACC Technology

In the second stage, a pilot survey was conducted first. Since the questionnaire is semi-structured, a pilot study was critical for the preparation of data collection (Yin 2011) and to ensure the reliability and validity of the final questionnaire survey. Eight industry experts (Table 1) with good knowledge in BIM, OSM and the NZBC were invited to complete the preliminary questionnaire, and their responses were then carefully analysed to find out (1) any inconsistency in the survey design, (2) any flaws in specific questions, and (3) any missing questions or pre-defined answers. The same experts were then invited to participate in semi-structured interviews (each lasting around 1.5 hours) to provide additional information and comments related to their answers. The interviews had two purposes. Firstly, they helped the research team understand the rationale and gain in-depth knowledge about participants' responses to further improve the questionnaire. Secondly, they provided in-depth insights that complemented the final questionnaire survey. Each interview was recorded properly and then transcribed.

Table 1. Interviewee profile (survey study)

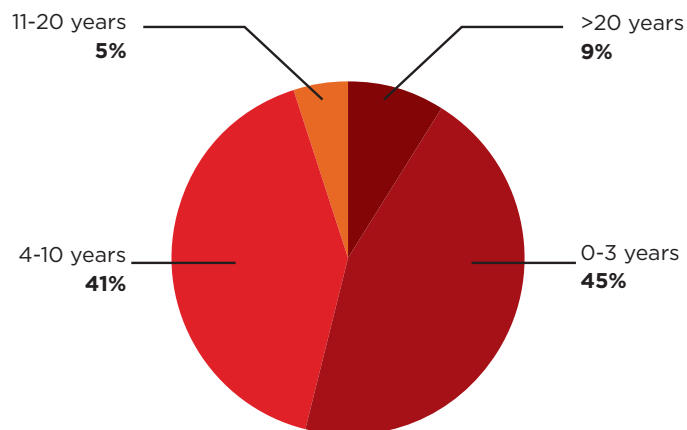
Interviewee No.	Position	Industry segment	Area of expertise
1A*	Director	Architect	National leading architect with >10 years of experience in both traditional and OSM projects.
1B	Director	Architect	National leading architect with >15 years of experience in both traditional and OSM projects.
1C	Director	Architect	National leading architect with >10 years of experience in both traditional and OSM projects.
1D	Senior Architect	Architect	A senior architect with >5 years of industry experience.
1E*	Director	Engineering Consultancy	National expert with >15 years of experience as civil/structural engineer.
1F*	Director	Manufacturer	International and national expert in NZBC and OSM. Held responsibilities for delivering multi-large OSM projects in NZ.
1G	Principal Urban Planner	BCA	National leading expert and practitioner in the NZBC relating to town planning.
1H*	BCA Officer	BCA	National expert in the NZBC and BIM, with nearly 10-year experience in assessing building consent applications.

*Note: * refers to that interviewees 1A, 1E, 1F and 1H also attended the focus group.*

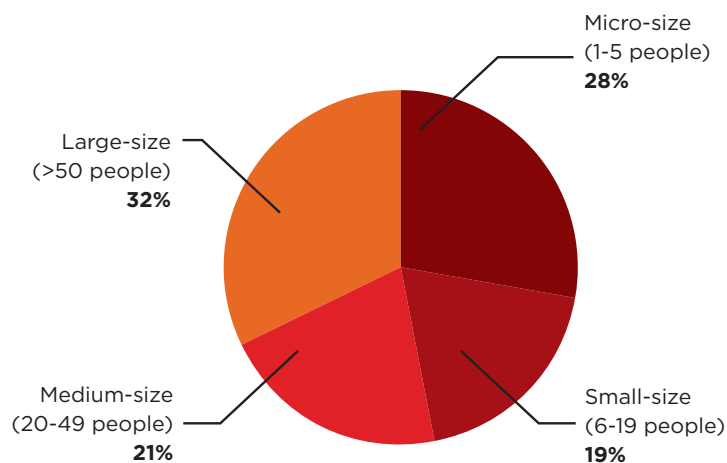
The questionnaire was then refined and distributed to the NZ OSM industry. Purpose-based convenience sampling strategy (Etikan et al. 2016; Javid et al. 2022) was employed to control the quality of the data collection. Participants were selected based on the following two criteria: (1) all participants are working in the OSM industry in NZ; (2) they are OSM professionals who also have good knowledge in digital design and construction (e.g. BIM, ACC). One hundred and sixty OSM professionals from OffsiteNZ, a professional OSM association in NZ, were invited by email for the questionnaire survey and 45 respondents completed the survey. The experience, roles and backgrounds of the respondents had a reasonably even distribution, as shown in Figure 2. Among the 45 respondents, 16% were from the government (including BCAs), 18% were clients, 23% were architects and designers, 14% were engineers, 27% were manufacturers, fabricators, suppliers, sub-contractors and builders, and 2% were real estate agents. After removing a response from a real estate agent, 44 valid responses remained with a valid response rate of 27.5%, which is higher than the general response rate of surveys (10%–15%) in Singapore (Teo et al. 2007) which has similar population size to NZ. The sample size and response rate were comparable to a previous study (Beach et al. 2020) that received 66 responses in the UK (with ten times the population of NZ). Therefore, the sample size was considered satisfactory for the analysis.

Figure 2. Respondents' Profile: (a) number of years the respondents have experience in the NZ OSM industry; (b) the approximate sizes of the respondents' companies; (c) the respondents' roles in OSM projects

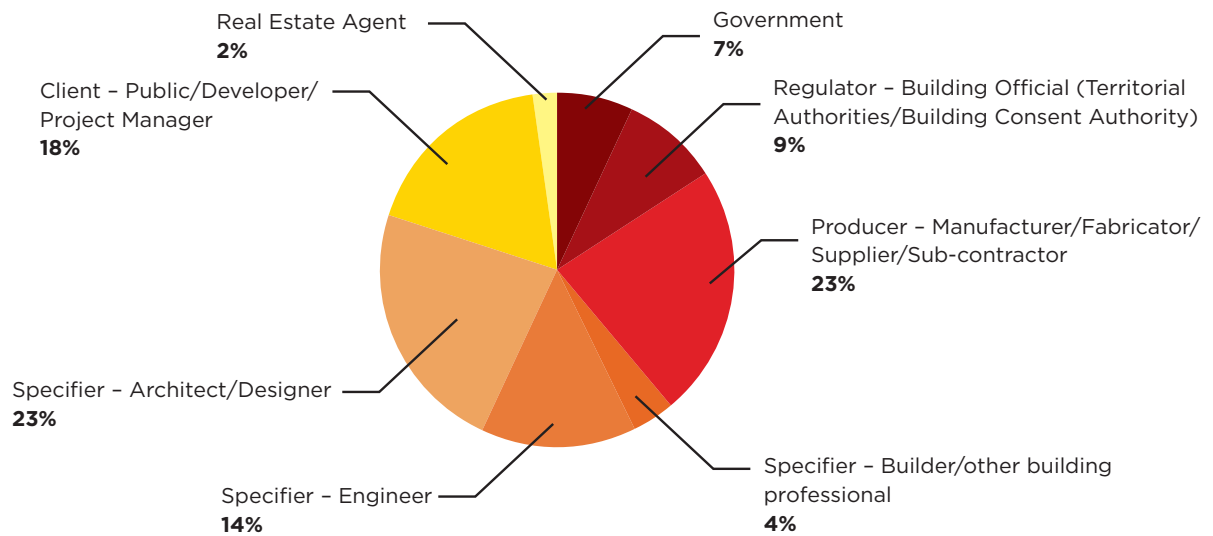
(a)



(b)



(c)



The survey results were analysed using the SPSS Statistics software (IBM 2021) and displayed as tables or charts. Nominal data obtained from multiple-choice and checkbox questions were analysed by descriptive analysis, such as percentages and frequencies. Ordinal data could be interpreted by assigning integers to the response categories to represent the level of agreement to certain statements and taking the median of the integers to show the overall trend (Harpe 2015). The qualitative answers to open questions were grouped based on respondents' perspectives on the problem. For questions where the qualitative answers had very clear categories, semi-quantitative analysis was performed to interpret the responses. The summary of the qualitative responses provides supportive evidence for the quantitative results.

3.3. Stage 3: Developing a strategic roadmap to facilitate ACC adoption

Stage 3 aimed to answer RQ3. It was conducted to learn about international efforts on ACC adoption, and to transfer evidence-based knowledge and experience to NZ in order to develop a strategic ACC adoption roadmap for the OSM industry. Stage 3 included (1) interviews, (2) conceptual roadmap development, and (3) focus group (FG).

Purposeful sampling (Palinkas et al. 2015) was used to identify and select interviewees who had rich knowledge and experience related to ACC adoption. To ensure the interview data could be situated within the context of this research, the selection of interviewees was governed by the following three sampling criteria: (1) the experts should have direct experience on the development or testing of at least a functional ACC prototype system that can fully or partly automate the regulatory compliance processes; (2) the experts should have real ACC adoption experience (e.g. the ACC system was tested in a pilot project); (3) the ACC adoption experience shared by the experts must have the involvement of multiple key stakeholders. A total of 16 individual interviews (each around 1 hour) was conducted through video conference with ACC experts from Australia, China, Denmark, Netherlands, NZ, Norway, Singapore, South Korea and United Kingdom. The profile of interviewees and key interview questions can be found in Table 2 and Table 3, respectively. The interview transcripts were sent back to the interviewees for checking, which is a critical technique for building credibility in qualitative research (Lincoln and Guba 1985). No major modifications to the transcripts were suggested. These interviews were grouped based on respondents' countries because each country has unique characteristics in terms of policy, building code, regulation system, building typology, building consent processes, stakeholder requirements, etc. The data for each country was initially studied separately such that the data could be refined using content analysis in two cycles of coding. The first cycle of coding was structural coding which resulted in defined codes from the data matrix being associated with multiple subcodes. The second cycle of coding was focused coding. Based on the results of the first coding, the most outstanding codes were identified, and themes were developed (Saldaña 2021). Once the data for each country was analysed and refined, a cross-country analysis took place following the recommendations of Miles et al. (2014).

Table 2. Interviewee profile (roadmap development)

Interviewee No.	Profession	Country	ACC experience
2A	Academic researcher	Australia	International leading ACC expert who was involved in the development of an early ACC system in Australia.
2B	Designer	China	Design engineer who was involved in a major ACC pilot project in China.
2C	BCA officer	China	BCA officer who was involved in a major ACC pilot project in China.
2D	Academic researcher	China	Emerging researcher with >3 years of ACC research experience.
2E	ACC technologist	China	National leading ACC expert who was involved in the development of ACC software in China.
2F	Academic researcher	Denmark	Emerging researcher with >4 years of ACC research experience.
2G	ACC technologist	Estonia	National leading ACC expert who was involved in the development of ACC software in Netherlands/Estonia.
2H	ACC technologist	Estonia	National leading ACC expert who was involved in the development of ACC software in Netherlands/Estonia.
2I	BCA officer	NZ	BCA officer who was involved in a major ACC pilot project in NZ and conducted a research project on ACC at master level
2J	Standard expert	NZ	National leading standardisation expert
2K	Standard expert	NZ	National leading standardisation expert
2L	Academic researcher	NZ	International leading expert with >30 years of ACC research experience
2M	OSM expert	UK	OSM expert who has project experience in both UK and NZ
2N	Academic researcher	Norway	International leading expert with >15 years of ACC research experience
2O	Academic researcher	Singapore	International leading expert who was recently involved in a major ACC development project in Singapore
2P	ACC technologist	Singapore	International leading expert with >20 years of ACC research and development experience
2Q	Academic researcher	South Korea	International leading expert with >14 years of ACC research and development experience
2R	Academic researcher	UK	International leading expert with >10 years of ACC research and development experience

Notes: Two interviews involved two interviewees (2G/2H and 2J/2K) each time. * refers to interviewee 2L also attended the focus group.

Table 3. Key interview questions

No.	Questions
1	What were the specific reasons motivating the development/use of ACC technology?
2	What were the challenges in promoting the use of ACC? How did you solve the problems?
3	What technology improvements will enhance the ACC adoption?
4	What were the top factors to the success of ACC uptake?
5	What were the main barriers that prevented ACC uptake?

Based on the content analysis of the interview data obtained from the previous step, a conceptual roadmap was proposed to improve the understanding of lessons learned from global ACC adoption. The roadmap specifically attempted to describe key actions in a timeline for facilitating wider ACC adoption.

To validate and refine the proposed roadmap, 9 industry experts in the positions of BCA officer, design directors, project manager and BIM specialist attended an FG. Five out of the 9 experts had participated in interviews in previous stages, and the rest of the experts were identified and invited for their good knowledge in BIM, OSM and the NZBC. The FG was held online through video conference for around three hours and focused on (1) finding missing and inappropriate items, and (2) improving the time-sequential relationship of suggested actions to finalise the roadmap. The experts were also asked to comment if there was any customisation needed to the roadmap for the NZ OSM industry. The discussion was recorded properly and then transcribed. All suggestions were extracted from the transcribed data and used to improve the roadmap. For instance, interviewee 2L suggested extending the action (Technology firms improve ACC maturity) to be included in all stages as technology is never perfect and always needs improvement. Interviewee 1H recommended removing the action (BCA to simplify building consent assessment) since this is more like an outcome rather than a prerequisite for ACC adoption. The improved roadmap was lastly emailed to all FG experts who were asked to check the roadmap and confirm no further changes were needed.

4. Survey Results: New Zealand Offsite Manufacturing Industry's Readiness on ACC Technology

4.1. The current BIM uptake in NZ OSM Industry

Table 4 shows the results of questions in terms of OSM professionals' general BIM adoption, the use of BIM for building code compliance and their awareness of BIM. The questions allowed respondents to rate from 0 (BIM is not used at all) to 10 (the whole process is 100% reliant on BIM). It can be seen that the OSM professionals had very different levels of adoption and understanding of BIM for their design process. Fifty-seven percent of respondents had no or very limited experience in using BIM for OSM design. However, 36% of them chose the score of 7 or higher, indicating that BIM had been integrated into their OSM design process and business. The discrepancies in the level of BIM use between different companies were also mentioned in the expert interviews. This can be explained by an observation that globally large firms had many more resources and better capacity to rapidly implement new applications of BIM and other digital innovations in construction than small and medium enterprises (SMEs) (Hong et al. 2019).

Table 4. Results of questions regarding general BIM adoption, the use of BIM for building code compliance and their awareness of BIM

Survey questions	Percentage of ratings					Median rating
	0-2	3-4	5-6	7-8	9-10	
The level of BIM adoption in current design process for OSM	48%	19%	7%	14%	22%	3
BIM can bring potential benefits to OSM	19%	5%	14%	25%	37%	7
The level of BIM currently used to assist in building code compliance checking	65%	2%	12%	14%	7%	1

The respondents' opinions on how much BIM could benefit the OSM design processes in terms of project quality and fast delivery were similar. On the perceived benefits of BIM in OSM projects, 76% of respondents suggested BIM will potentially bring benefits to OSM projects, and the median of all ratings was 7, indicating a distinct trend of a high level of recognition of the benefits of BIM. Similarly, good awareness of BIM use in future OSM projects, such as 3D visualisation and coordination, was observed from all interviewees. However, interviewee 1F pointed out that more advanced applications of BIM were not widely adopted by subcontractors and manufacturers; additionally, potential conflicts on ownership of digital data assets needed to be further addressed.

So far, the use of BIM for assisting building code compliance (e.g. peer review within design firms, submission of BIM-based design solutions to BCAs for checking) has not been adopted broadly, and the benefits of BIM-based building code compliance have not been recognised by the OSM industry. Sixty-five percent of respondents scored 2 or less (median is only 1 out of 10) when asked what percentage BIM is used for building code compliance in their businesses and to what extent they believe BIM will be helpful for building code compliance in the future. It can be determined from interview results that (1) there is a lack of BIM-based building code compliance solutions ready for the OSM industry, (2) the BCAs have not formally begun to accept the submission of OSM designs

in BIM and it is unknown whether the BIM-based submission will speed up building consent process, and (3) there are no proven case studies about BIM-based building code compliance in NZ that could be used by other OSM companies to shorten their learning curves.

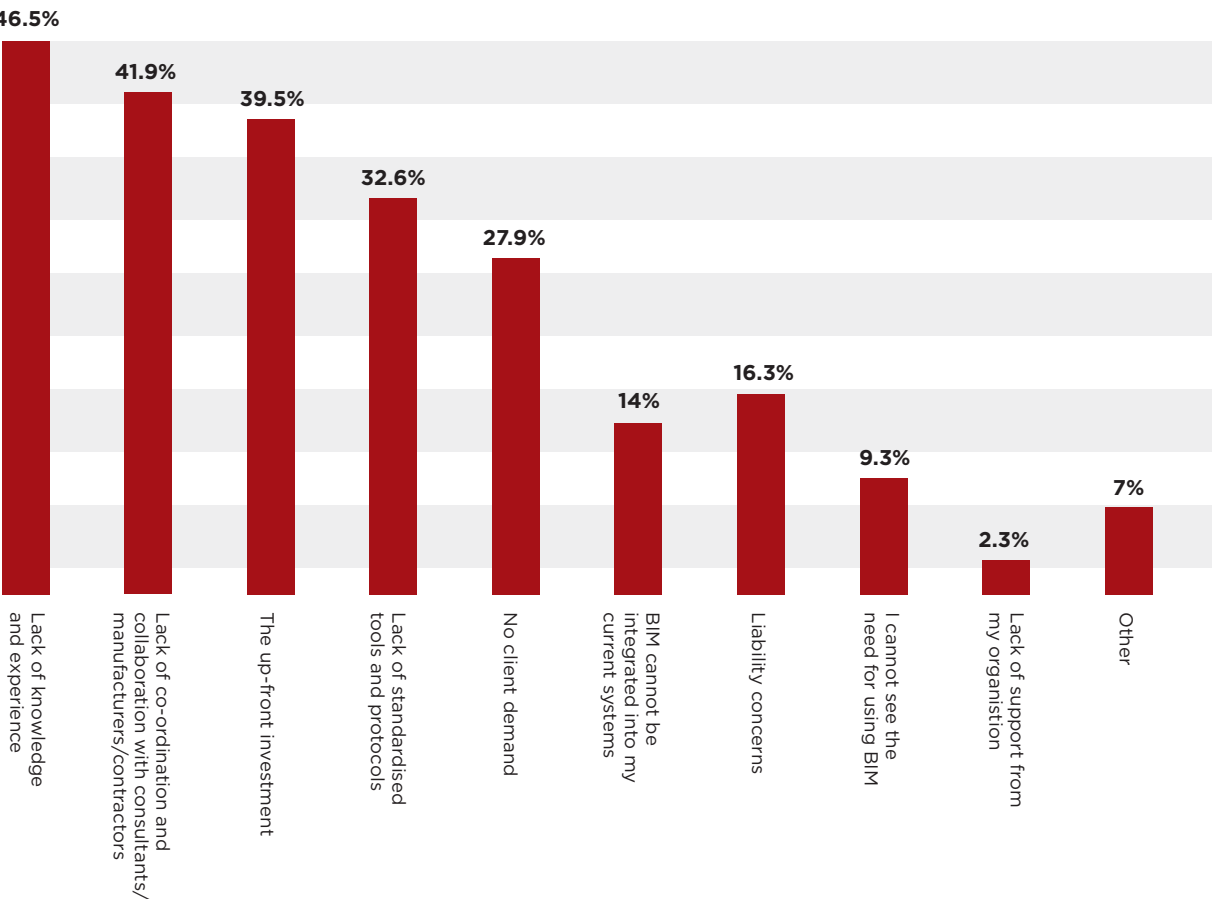
Most of the respondents (79%) answered they would use or are using BIM if any BIM-based ACC solution exists. The results indicate a positive trend that the continuous development and adoption of potential BIM-based ACC technologies will facilitate a wider BIM adoption in OSM in the near future.

Figure 3 shows the survey respondents' opinions on critical barriers to BIM adoption in the NZ OSM industry. It can be found that the most critical barriers in terms of low BIM implementation rate in OSM projects include lack of knowledge and experience (46.5%), lack of coordination and collaboration with stakeholders (41.9%), large up-front investment needed (39.5%), lack of standardised tools and protocols (32.6%) and no client demand (27.9%). Interviewee 1B explained the low adoption of BIM as:

“The current use of BIM for code compliance checking is a manual examination process, which mainly relies on checking accurate 3D visualisation. In order to achieve the required level of details, a huge amount of input is needed in building up the 3D models, which leads to extra costs and may not be an economical solution for them at the moment.” (Interviewee 1B)

Interviewee 1H indicated that the BCA could not directly check the BIM models for building consent but would encourage the submission of BIM-based digital data as an additional dataset to assist their decision making in the foreseeable future. It was admitted by interviewee 1H that the BCA officers across NZ had very different abilities in understanding and checking BIM data. Further training to improve BCA's capabilities in the use of BIM is necessary.

Figure 3. Results for question regarding the most critical barriers limiting BIM adoption in the NZ OSM industry.



4.2. NZ OSM Industry's Readiness and Awareness for ACC

The survey received 25 quality responses to the open-ended question regarding the current solutions the respondents have used or suggestions they may have to deal with compliance checking challenges. It can be seen from these results that there are currently no commercial solutions used by the OSM industry that can either fully- or semi- automate the building code compliance processes. As an alternative, a commonly used industry practice to reduce the risk of OSM projects failing to comply with building code is through third-party assurance. Additionally, three suggestions on relevant legal procedures, cross-disciplinary collaboration and professional competency were mentioned that could improve the existing building code compliance process towards the approval of a building consent application (Table 5).

Table 5. Received suggestions that can improve the existing building code compliance process towards gaining a building consent

No.	Comment(s)
1	Simplify and speed up the building code compliance checking during the process of building consent assessment at BCAs
2	Improve cross-disciplinary coordination and communication within and across organisations to avoid unnecessary iterations and to demonstrate a better integrated OSM building product
3	Improve the consistency in understanding the building code among BCAs

Although ACC for OSM projects has not started, the importance of having such technologies is widely recognised by the survey respondents and interviewees. As shown in Figure 4, the majority of the respondents (71%) either expressed their interest in ACC or noted that they have already developed plans to automate the building code compliance process. They also provided additional comments on the desired features or changes coming from employing ACC for better building code compliance (Table 6).

Figure 4. Results for question regarding the demand and plans on automating the compliance checking process

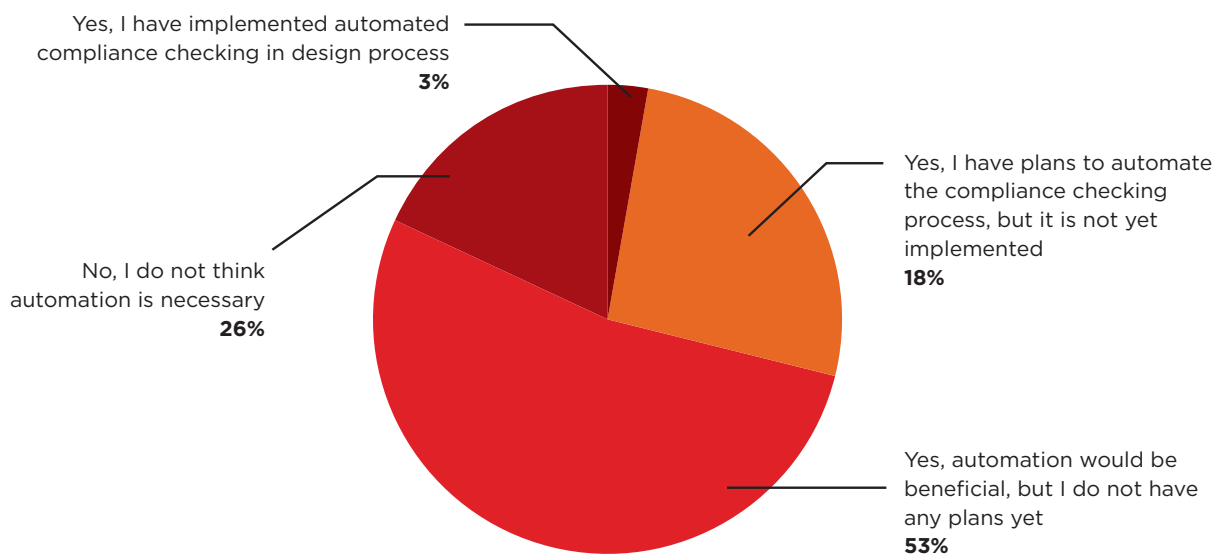
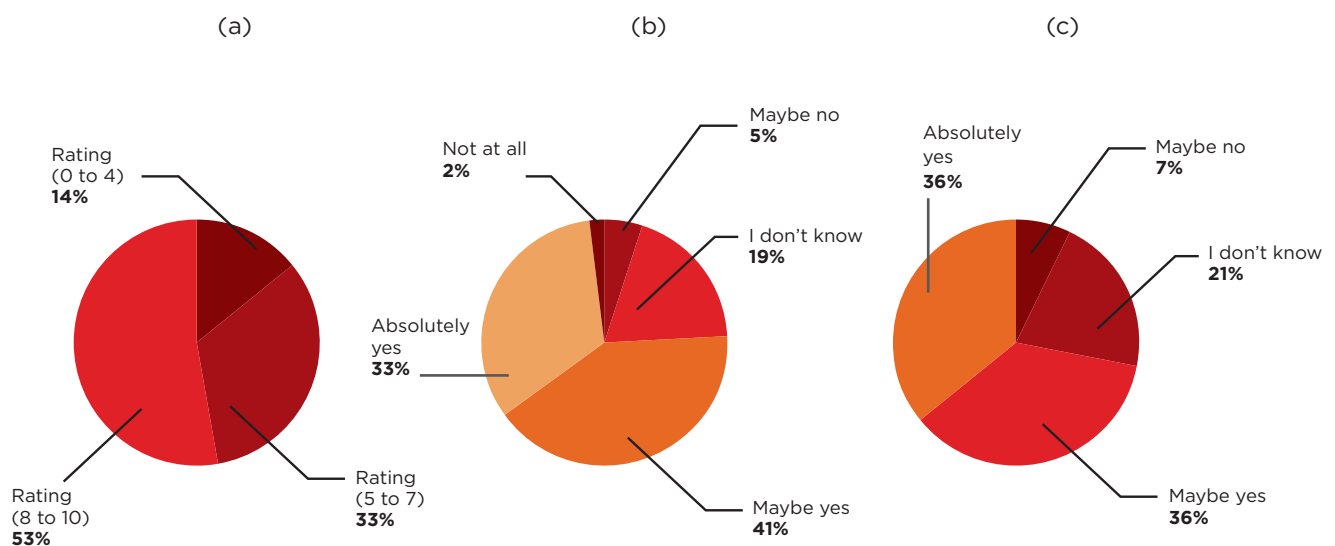


Table 6. Desired features or changes coming from use of ACC for better building code compliance

No.	Comment(s)
1	Direct interaction with the BIM model and a common data environment would allow inputs to be easily accessed and shared by all parties, which could vastly improve the efficiency of the consenting process.
2	Synchronised design changes and comments between designers and building consent specialists can reduce the significant amount of paperwork involved and avoid ambiguities in communication.
3	A set of minimum data requirements and a required compliance information list will facilitate standardising the compliance checking process, as OSM often involves Design for Manufacture and Assembly (DfMA) details which are outside the scope of BCA's pre-established acceptable solutions.
4	Once the ACC technology is ready and mature, BCA's consenting processes and requirements should be updated accordingly to encourage greater use of such automated technologies.

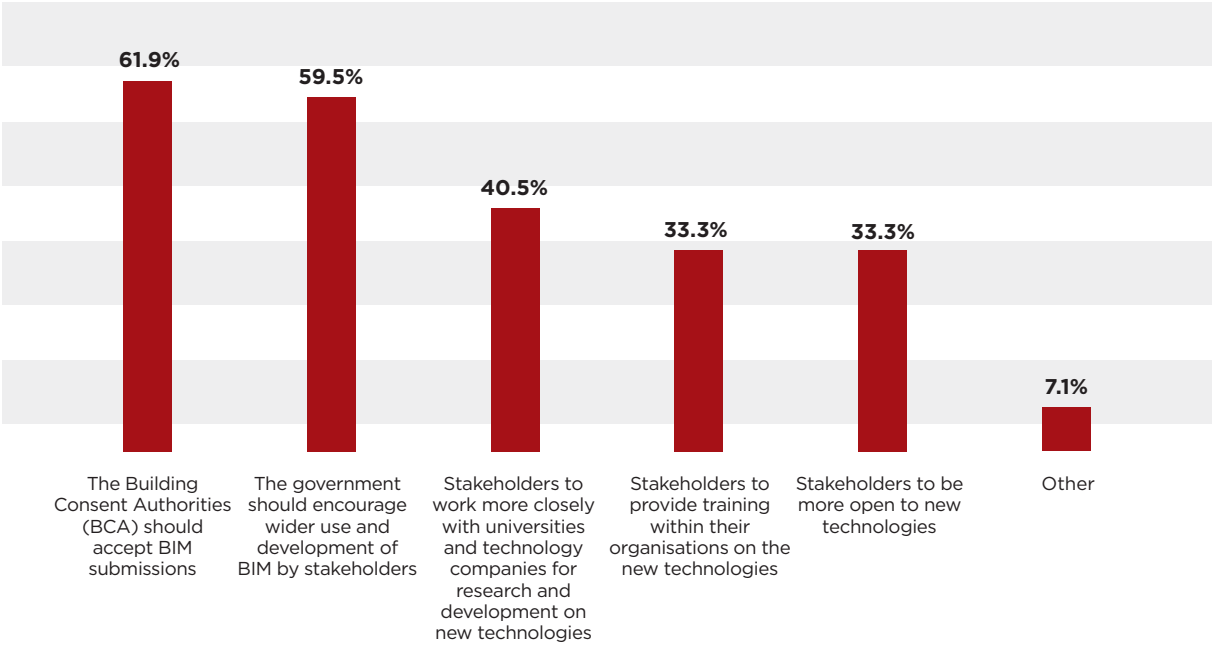
The level of perceived benefits of adopting ACC technology for OSM projects, businesses and industry were evaluated. As shown in Figure 5, 64.3% of respondents suggested that ACC technology would bring substantial benefits to OSM projects and improve quality, cost control and delivery. Thirty-one respondents (74%) agreed that automating the building code compliance process would bring tangible and intangible benefits to their organisations or companies, and 30 respondents (72%) held a view that if such automation technologies existed, it would expedite the broader development and implementation of all levels of OSM for building construction in NZ. The interviewees also agreed that automating or simply providing shortcuts to the current consenting process could be hugely beneficial to their projects.

Figure 5 Survey results regarding the perceived benefit of the automated building code compliance technology for (a) improving OSM quality, cost control and delivery, (b) the respondent's organisations or companies, and (c) facilitating greater adoption



As to the critical barriers that prevent ACC adoption (Figure 6), 61.9% of survey respondents suggested that BCAs have not begun accepting BIM submissions in the building consent process, and 59.5% of respondents suggested that a higher level of BIM usage was a prerequisite for ACC technologies. In addition, 40.5% of respondents maintained that an open attitude toward new technologies and more collaboration with research and development (R&D) professionals could help stakeholders recognise and accept ACC, and integrate ACC technologies into existing work processes. One-third of respondents believed training and education are critical for the professionals so they can upgrade their knowledge and have the right skills to use ACC.

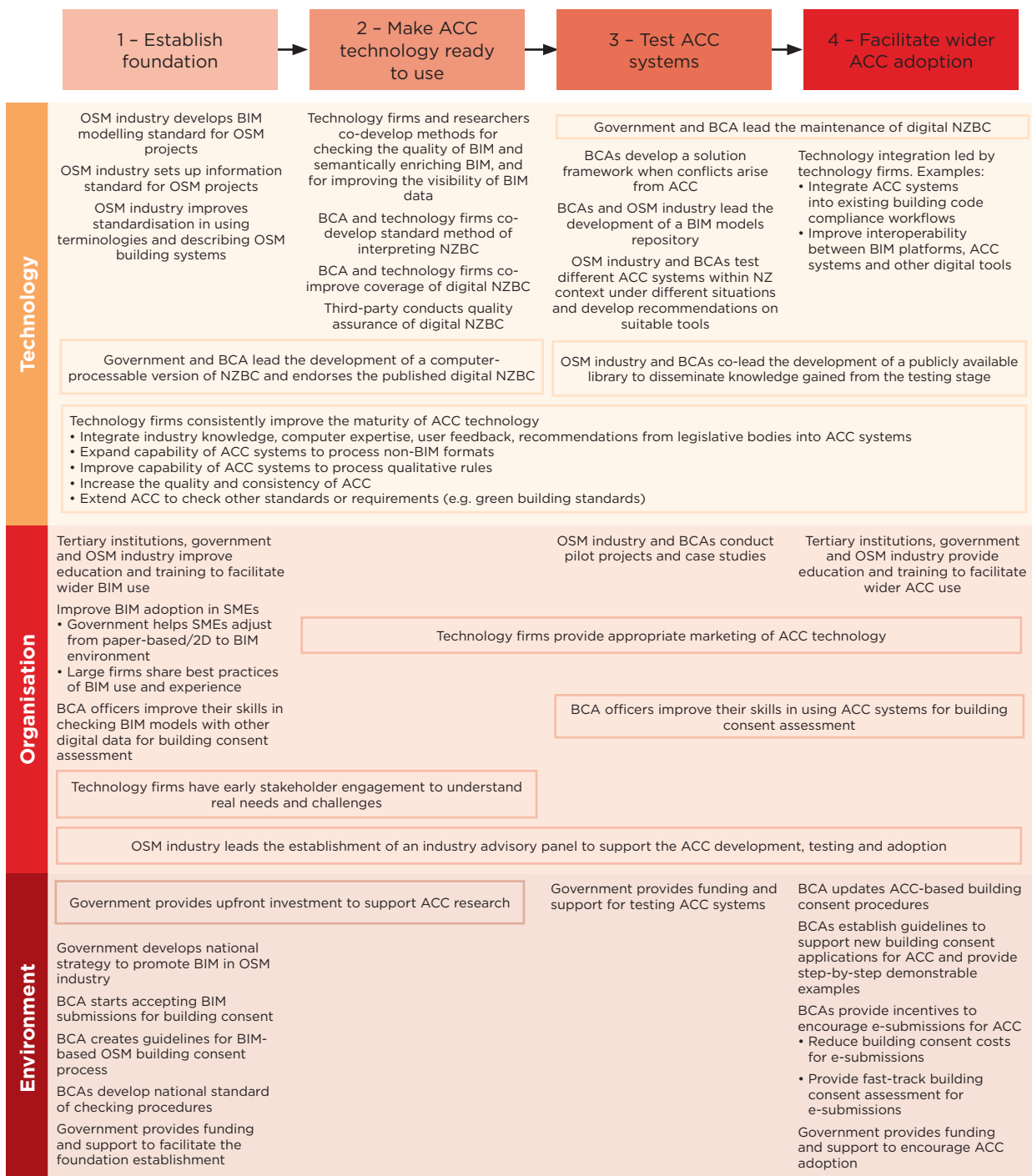
Figure 6. Critical barriers to ACC technology adoption



5. An ACC Adoption Roadmap for New Zealand Offsite Manufacturing Industry

The final roadmap is presented in Figure 7, describing key actions that can facilitate wider ACC adoption within NZ OSM industry in three contexts, according to the Technology-Organisation-Environment (TOE) framework (Tornatzky et al. 1990). The “Organisation” in this study refers to the NZ OSM industry. The “Technology” context includes actions that are relevant to ACC-related technologies. The “Environment” context consists of regulatory environment and external support by the government. A total of thirty key actions was identified. Their description and justification can be found in Tables 7-9.

Figure 7. A roadmap to facilitate the adoption of ACC in NZ OSM industry



Time

Table 7. Roadmap – “Technology” actions

No.	Stage(s)	Suggested action	Description and justification
1	1	OSM industry develops BIM modelling standard for OSM projects	To address the inconsistency issues (e.g. naming objects) when different people are creating the BIM models; To provide good-quality BIM models for ACC.2
2	1	OSM industry sets up information standard for OSM projects	To make sure the BIM models contain the essential and accurate data in a structured way. Such efforts will help minimise modelling efforts and reduce confusion, making ACC easier to be accepted by end users.
3	1	OSM industry improves standardisation in using terminologies and describing OSM building systems	Different OSM systems exist in NZ. A standard way of describing OSM systems that are slightly different will avoid confusion. This is particularly important for offshore offsite when the whole or part of the OSM buildings are imported from overseas.
4	1-2	Government and BCA lead the development of a computer processable version of NZBC and endorse the published version	<p>Government and BCAs are suggested to convert normative provisions conveyed in NZBC into machine-processable forms. After quality assurance has been conducted on the digital version of NZBC by third parties, an official endorsement by the government is necessary to make the published digital NZBC accepted by the OSM industry.</p> <p>Most recently, a project to translate a number of priority consenting documents from the NZBC and associated normative standards into open legal interchange standard LegalRuleML (LRML) was undertaken by the University of Auckland in 2019, under the NZ government-funded National Science Challenge: Building Better Homes, Towns, and Cities (NSC BBHTC) (Dimyadi et al. 2020).</p> <p>In the future, there is also a strong need to convert the guidelines and non-regulatory compliance documents for OSM projects (e.g. (Auckland Council 2020; James et al. 2017; PrefabNZ 2018)) into machine-readable forms for ACC. For example, the pre-agreed product, erection and interfacing tolerances can be checked in BIM-based design so that both offsite and onsite teams can have confidence to build the project as designed.</p>
5	1-4	Technology firms consistently improve the maturity of ACC technology	There is always room to improve the technology. As a result, this action lasts throughout the whole timeline. Suggestions include (1) integrate industry knowledge, computer expertise, user feedback, and recommendations from legislative bodies into ACC systems, (2) expand the capability of ACC to process non-BIM formats and qualitative rules, (3) increase the accuracy and consistency of ACC, and (4) extend ACC to check other standards and requirements (e.g. green building standard).
6	2	Technology firms and researchers co-develop methods for checking the quality of BIM and semantically enriching BIM, and for improving the visibility of BIM data	To have satisfactory ACC accuracy, the BIM model to be checked needs to have correct and enough information. However, BIM data in real world is often variable. To address this challenge, some recent developments in BIM quality check (Choi and Kim 2013), semantic enrichment (Bloch and Sacks 2018), and data visualisation and visibility (Liu et al. 2016) might be further developed to make the BIM data more machine-processable for ACC purpose.

No.	Stage(s)	Suggested action	Description and justification
7	2	BCA and technology firms co-develop standard method of interpreting NZBC	While the government is leading the development of digital NZBC, it will be a problem that people from different agencies interpret the building code differently. A consistent and standard method of interpreting NZBC is expected.
8	2	BCA and technology firms co-improve the coverage of NZBC	The challenging aspect of checking qualitative normative provisions needs to be addressed.
9	1	Third-party conducts quality assurance of digital NZBC	The quality of the digital NZBC needs to be checked and assured by third parties.
10	3-4	Government and BCA lead the maintenance of digital NZBC	Since building code is updated and revised regularly, the digital version of NZBC needs to be updated accordingly.
11	3	BCAs develop a solution framework when conflicts arise from ACC	In case there are any conflicts or errors generated unexpectedly by ACC, there is a need to develop a standard solution framework to allow human experts to be involved to address the conflicts.
12	3	BCAs and OSM industry lead the development of a BIM models repository	BIM models in this repository are obtained from real OSM projects and can support the testing of different ACC systems by different agencies.
13	3	OSM industry and BCAs test different ACC systems within NZ context under different situations and develop recommendations on suitable tools	ACC systems' suitability for NZ OSM projects for specific part of NZBC under different scenarios is unknown. Having these available systems tested in NZ and providing recommendations about their strengths and weaknesses will be important to help OSM industry reduce trial costs.
14	3-4	OSM industry and BCAs co-lead the development of a publicly available library to disseminate knowledge gained from the testing stage	To help other OSM stakeholders shorten their learning curves and contribute to facilitating the whole OSM industry to adopt the new technology.
15	4	Technology integration led by technology firms	Examples include, (1) integrate ACC systems into existing building code compliance workflows, and (2) improve interoperability between BIM platforms, ACC systems and other digital tools.

Table 8. Roadmap – “Organisation” actions

No.	Stage(s)	Suggested action	Description and justification
1	1	Tertiary institutions, government, and OSM industry improve education and training to facilitate wider BIM use	To help OSM stakeholders, especially downstream project parties such as sub-contractors, understand the benefits and values of BIM.
2	1	Improve BIM adoption in SMEs	For a small country like NZ, most OSM players are SMEs. The government can help SMEs adjust from paper-based to BIM environments. Without the support from the government, it will take a long time for SMEs to evolve their businesses. Large firms can also share best practices of BIM use and experience.
3	1	BCA officers improve their skills in checking BIM models with other digital data for building consent assessment	BCA officers are expected to be capable of processing e-submissions in the format of BIM.
4	1-2	Technology firms have early stakeholder engagement to understand the real needs and challenges	To make sure the ACC technology to be developed can address real and practical needs and will be bought by the OSM industry.
5	1-4	OSM industry leads the establishment of an industry panel or advisory group to support ACC development, testing and adoption	Members of the industry advisory group can not only support ACC research, testing and wider adoption but use their knowledge, experience and skills to help make strategic decisions.
6	2-4	Technology firms provide appropriate marketing of ACC technology	A common problem for new technology adoption is that the market tends to oversell or promise functions that are not yet fully developed. An appropriate marketing strategy will contribute to building the trust between ACC technology and end users.
7	3	OSM industry and BCAs conduct pilot projects and case studies	Multiple pilot projects and case studies can help test the ACC technology for real OSM projects in NZ. The pilot and case study can be conducted on a small scale for different OSM types and tested for different sections of the NZBC. According to (Ciribini et al. 2016), benefits of this action include: (1) to test the new technology in solving real problems and gain experience for further technology improvement, (2) to gain implementation experience, and (3) to validate the potential benefits of the new technology.

No.	Stage(s)	Suggested action	Description and justification
8	3-4	BCA officers improve their skills in using ACC systems for building consent assessment	BCA officers are expected to integrate ACC into their existing building consent assessment workflows and become familiar with ACC systems.
9	4	Tertiary institutions, government and OSM industry provide education and training to facilitate wider ACC use	To help OSM stakeholders understand the benefits and values of ACC.

Table 9 Roadmap – “Environment” actions

No.	Stage(s)	Suggested action	Description and justification
1	1	Government develops national strategy to promote BIM in OSM industry	Important lessons can be learned from the successful national deployment of BIM in Finland and UK, which indicates a national BIM strategy can facilitate the evolvement of the building and infrastructure sectors (Aksenova et al. 2019; Piroozfar et al. 2019).
2	1	BCAs start accepting BIM submissions for building consent assessment	BCAs are suggested to consider improving their capabilities for processing BIM models in conjunction with other digital data.
3	1	BCAs create guidelines for BIM-based OSM building consent process	Similar attempts have been already observed from overseas, which can provide important lessons for NZ. For example, the US General Services Administration (GSA) funded major construction projects are required to submit BIM-based designs for spatial program reviews and spatial data management submissions, where GSA design teams can use BIM to validate spatial program requirements (e.g. area, efficiency ratios) (Abd Samad et al. 2018). GSA published a guideline in 2015 to support this program (GSA 2015).
4	1	BCAs develop a national standard of checking procedures	All BCAs agree on a standard checking procedure.
5	1-2	Government provides upfront investment to support ACC research	To address the challenge that the industry does not have funds to support ACC research and development.
6	1	Government provides funding and support to facilitate the foundation establishment	The foundation establishment will benefit all stakeholders. Government is recommended to provide support and play a driving role in this process.
7	3	Government provides funding and support for testing ACC systems	Funding and support from government can help industry transform and evolve.
8	4	BCA updates ACC-based building consent procedures	The building consent workflows should be updated accordingly after ACC systems are used.

No.	Stage(s)	Suggested action	Description and justification
9	4	BCAs establish guidelines to support new building consent applications for ACC	The new guidelines should be thorough enough and contain step-by-step demonstrated examples, which can be easily learned by the industry. Particularly, it should include content such as how to prepare the BIM models, what level of details should the BIM include, and what minimum digital data requirements should be for building consent applications.
10	4	BCAs provide incentives to encourage e-submissions for ACC	For instance, e-submission for building consent assessment can have lower costs and be processed faster.
11	4	Government provides funding and support to encourage ACC adoption	To help OSM industry transform and evolve.

The timeline of the proposed roadmap is divided into four stages, i.e. (1) establish foundation, (2) make ACC technology available to use, (3) test ACC system, and (4) facilitate wider ACC adoption. In the first stage, the foundation needs to be well established to support broad adoption of ACC systems in NZ OSM industry. Once the foundation is established, the ACC solution is expected to be further advanced and improved in the second stage to have, at least, limited capability in real scenarios. The third stage, “test ACC systems”, is a piloting phase where ACC systems are tested in real OSM under different scenarios to gain experience and build trust. There is a need to note that any experience and lessons learned from this phase can be very valuable for improving the maturity of the ACC technology, which leads to improved and customised ACC solutions to the NZ OSM environment. In the piloting stage, ACC systems might also be tested and improved for specific OSM requirements. For instance, prefabricated components or whole buildings can be manufactured in local or offshore factories and transported to different sites, where ACC may help identify non-certified materials and check if the products meet regulatory requirements by local councils. The designers may also take advantage of ACC to check erection tolerances of prefabricated components, or whether the selection of a specific type of OSM house for the site in the largest city of NZ, Auckland, meets the zoning requirements according to the latest Auckland Unitary Plan (Auckland Council 2016). For the construction of OSM buildings, the transportation of OSM components or buildings is often subject to size limitations, and these projects may require more space on site. ACC might be used to check construction site planning against these limitations. The final stage is to facilitate wider adoption of the ACC technology in NZ OSM industry.

6. Discussion

6.1. Contribution to knowledge

Firstly, this study examined the BIM adoption in NZ OSM industry (RQ1). Although there are several papers that investigated BIM adoption in NZ for green building (Doan et al. 2019), and general construction (BIM Acceleration Committee (BAC) 2019a), no literature has been found on BIM adoption in the OSM industry in NZ. The findings indicate that there is a large discrepancy in the level of BIM implementation among different OSM firms in NZ (Table 4). According to the PrefabNZ Capacity and Capability Report (PrefabNZ 2018b), 59% OSM companies in NZ are small businesses with less than 20 employees. A study by Hong et al. (2019) suggested SMEs are generally much slower in BIM uptake than large firms; however, improving the BIM awareness and skills of SMEs may significantly increase the BIM adoption rate in the NZ OSM industry. Relevant experience and lessons might be learnt from other developed countries such as UK (Lam et al. 2017) and Australia (Hosseini et al. 2016). Although most ACC systems largely rely on BIM data, the current NZ BIM implementation is not ready to further support the adoption of ACC systems because (1) there is a lack of mature ACC technology, (2) no proven case studies exist, and (3) BCAs have not formally begun to accept and process BIM submissions for building consent process. A number of challenges limiting BIM implementation in NZ were received (Figure 3), with the top three being (1) lack of knowledge and experience, (2) lack of coordination and collaboration with consultants, manufacturers, contractors, and (3) up-front investment.

Secondly, this report explored the NZ OSM industry's awareness and demand for ACC systems (RQ2). The findings confirm that automating the building code compliance is in demand (Figure 4), especially to support the building consent processes. ACC has been considered as a task for designers and BCAs; however, the potential value of the wider application of ACC to the lifecycle of OSM projects was ignored by most survey participants. Compared with traditional linear construction, OSM is a more complex system requiring high-quality designs at the beginning (no later design changes are allowed), early preparation of the site for storage of modular components, and simultaneous running of the logistics of both offsite and onsite work. There is a need to further develop and employ ACC solutions to check both the mandatory NZBC and other non-regulatory compliance requirements (e.g., certification of materials, zoning requirements, manufacturing and erection tolerances, site restrictions, transportation) for OSM projects. Although most OSM stakeholders are open to both BIM and ACC systems, the industry itself is reluctant to evolve due to being limited by several factors such as huge upfront investment, big learning curve, technology risks, and failure in convincing other stakeholders on the chains to update their workflows. Several ACC approaches exist; however, none of these has been tested for checking real OSM projects in NZ. From Table 6, the OSM industry expected that in the future, (1) ACC systems could be integrated into the current BIM workflow and BIM-based information management system (e.g. CDE), (2) ACC systems could synchronise design changes and comments between designers and BCAs, and (3) a set of minimum data requirements should be provided to the practitioners for ACC purposes. Additionally, an important finding is that BCA and other government departments can play an important role (through proper policies, programmes, and guidelines) in the process of transforming the OSM industry to adopt ACC technologies, which may significantly shorten the building consent processes.

Thirdly, in response to **RQ3**, a high-level roadmap (Figure 7) was proposed to describe key actions in the contexts of Technology, Organisation and Environment that can facilitate the wide adoption of ACC technology in NZ OSM industry. The timeline of the roadmap is divided into four stages: (1) establish foundation, (2) make ACC technology ready to use, (3) test ACC systems, and (4) facilitate wider ACC adoption. The findings highlight that facilitating the wide adoption of ACC systems for NZ OSM industry requires a systematic collaboration among all stakeholders rather than relying on technological development or changes made at the individual level. The government has driving power to impact the innovation environment and is expected to provide funding and policy to support the development, testing and use of ACC technology. A joint effort is needed among the government, OSM industry and technology firms to continuously improve the technology, customise it to be suitable for the NZ context, and gain valuable experience through testing the technology. It is also critical to explore the interpretation of the NZ performance-based building code for computability and to test the ACC technology in real NZ projects to gain valuable lessons and experience. Furthermore, upskilling the OSM stakeholders through education and training can eventually lead to the wider adoption of ACC systems.

6.2. Practical Implications

A number of practical implications can be drawn for the OSM industry in NZ. Firstly, the survey results confirm that the BIM adoption rate is still relatively low in NZ OSM industry. With the understanding that BIM data is a prerequisite for most modern ACC systems and that the OSM industry needs to be ready for BIM technology before ACC systems can be widely used, the development of appropriate national strategies is necessary to guide the whole NZ OSM industry to better accept and adopt BIM. Secondly, one major driver of adopting ACC systems for the NZ OSM industry is to speed up the building consent process. Unless the direct benefits are predictable, the industry will be reluctant to invest extra time and resources to use ACC systems. However, the government is slow to take up this change for various reasons. At this stage, BCA officers across NZ have different levels of understanding of BIM and ACC, and variable technical competency in processing BIM models and using ACC systems for building code compliance checking. Thus, the government, particularly BCAs, needs to level up their knowledge and capabilities to meet a growing need for ACC from the industry. Finally, Hong et al. (2019) pointed out that SMEs often lack resources and capabilities to adopt digital innovations in the construction industry. As a result, additional attention needs to be paid to SMEs, the major players in the NZ OSM industry. Different OSM stakeholders can, for example, collaborate to test the feasibility of ACC systems. Lessons learned from pilot projects and case studies can be shared to reduce the learning costs for other OSM stakeholders.

6.3. Limitations

Two limitations exist in this study. Firstly, the sampling size of the first-stage survey was relatively small. This was partly because NZ has a small OSM industry, which made it difficult to find many experts with adequate knowledge of OSM in relation to BIM and building code compliance practices. The sample size and response rate were comparable to a previous study (Beach et al. 2020), which received 66 responses in UK. As a remedy, this study followed a strict selection process on target participants and tried to find experts from different chains of OSM, e.g., consultancies, manufacturers, and BCA. To enrich the closed questionnaire responses, add qualitative insights and validate the collected dataset, eight semi-structured interviews were used. Secondly, this study did not consider variables such as cultural and social factors, which might be significant factors to individual OSM companies considering ACC adoption.

7. Conclusions

Given the growing demand for integrating ACC into OSM projects, this report firstly examined NZ OSM industry's awareness and readiness for ACC, and then learned from global lessons and developed a high-level ACC adoption roadmap for the NZ OSM industry. The results show that the professionals see the potential benefits of employing ACC to reduce risks, and improve productivity and project delivery for OSM projects; however, the foundation for ACC adoption has not been established. The roadmap suggested key actions in the contexts of Technology, Organisation and Environment can lead to broader ACC adoption in the NZ OSM industry. Apart from improving the maturity of ACC, other technology actions include establishing standards for OSM systems and BIM models, developing machine-processable NZBC, testing ACC systems in real OSM projects and improving their suitability to NZ context, and integrating ACC into existing workflows. The organisation context requires engaging stakeholders at an early stage, improving BIM use rate (especially for SMEs), having an appropriate marketing strategy, improving BCA officers' knowledge and skills through education and training, and conducting pilot projects and case studies. The roadmap also indicates that the government could play a leading role in influencing the "environment" of ACC adoption through offering funding and support for ACC research, testing and use and providing incentives and guidelines for BIM-based e-submissions and ACC-based building consent assessment. Overall, this study complements previous technology-focused efforts and enhances our understanding on non-technology factors that influence ACC adoption. Future research may consider investigating the actions in the roadmap at a finer level since each action identified is a significant task and challenge.

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