Case Study

Investigating the New Zealand Off-Site Manufacturing Industry's Readiness for Automated Compliance Checking

Yang Zou, Ph.D.[1]; Yuqing Wu[2]; Brian H. W. Guo, Ph.D.[3]; Eleni Papadonikolaki, Ph.D.[4]; Johannes Dimyadi, Ph.D.[5]; and Sze Nga Hung[6]

Abstract: Numerous automated compliance checking (ACC) approaches have been developed over the last half of the twentieth century. However, little is known as to how well the ACC technology has served the off-site manufacturing (OSM) industry from the end users' perspective. This paper aims to measure the New Zealand (NZ) OSM industry's awareness and readiness for ACC and explore a pathway toward wider ACC adoption. It first reports on a survey study in NZ with 44 valid survey responses. It then proposes a high-level roadmap with key actions that can facilitate wider ACC adoption through 16 interviews with international ACC experts and a focus group with nine local OSM stakeholders. The results show that although there is a high demand for automating compliance processes, the OSM industry, especially small and medium enterprises, are not ready to adopt the ACC technology. Suggestions to address this include (1) establish the foundation for broad ACC adoption; (2) boost the development of the ACC technology to expedite its maturity, (3) test the ACC technology under different scenarios and customize it for the NZ context; (4) encourage the government to provide funding and policy support; and (5) promote education and training of both building information modeling (BIM) and ACC to OSM stakeholders. The results can provide software vendors with valuable information about user expectations and requirements to develop ACC products that can better serve NZ OSM projects, and help OSM stakeholders in NZ and countries with similar economic and regulatory structures to understand the technological and nontechnological gaps to better prepare for the ACC technology adoption. **DOI: 10.1061/(ASCE)CO.1943-7862.0002384.**

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Introduction

Off-site 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 utilization and allowing the off-site production and on-site 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 recognized as a promising solution to address the shortfall of affordable housing demand globally (Thompson 2019). With the rapid development of advanced information technology (IT) in recent years, numerous efforts started employing building information modeling (BIM), which refers to the collaborative process of creating, sharing and utilizing information of the building life cycle (Eastman et al. 2011), in OSM projects. The integration of BIM and OSM brings benefits such as improving information exchange and modeling (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 prioritize the development and use of OSM (MBIE 2018). However, the benefit of speedy delivery of OSM projects cannot be fully realized due to current bottlenecks with manual compliance checking processes, which are labor 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 the project delivery timing. Undesired iteration cycles can be a major cause of project delays and cost increases in

[1]Dept. of Civil and Environmental Engineering, Univ. of Auckland, 20 Symonds St., Auckland 1010, New Zealand (corresponding author). ORCID: https://orcid.org/0000-0001-6150-6126. Email: yang.zou@auckland.ac.nz

[2]Dept. of Civil and Environmental Engineering, Univ. of Auckland, 20 Symonds St., Auckland 1010, New Zealand. Email: ywu453@aucklanduni.ac.nz

[3]Dept. of Civil and Natural Resources Engineering, Univ. of Canterbury, 69 Creyke Rd., Christchurch 8041, New Zealand. ORCID: https://orcid.org/0000-0002-1475-4618. Email: brian.guo@canterbury.ac.nz

[4]Bartlett School of Sustainable Construction, Univ. College London, 1-19 Torrington Place, London WC1E 7HB, UK. Email: e.papadonikolaki@ucl.ac.uk

[5]Codify Asset Solutions (CAS), Auckland 1010, New Zealand. ORCID: https://orcid.org/0000-0002-0004-1131. Email: jdimyadi@cas.net.nz

[6]Dept. of Civil and Environmental Engineering, Univ. of Auckland, 20 Symonds St., Auckland 1010, New Zealand. Email: shun782@aucklanduni.ac.nz

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construction planning (Preidel and Borrmann 2016). Additionally, OSM is a nonlinear 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 for storage of modular components, simultaneously running of logistics, and both off- and on-site work (PrefabNZ 2018b). Consequently, OSM needs to not only meet the performance outcomes of the NZBC, but must 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 predefined 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. Because 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 article is organized as follows. The next section reviews the 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 sections present discussions and conclusions of the research findings.

Background and Literature Review

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

OSM and BIM

Due to an increased demand for the speedy delivery of new buildings, OSM has experienced steady growth in NZ since the beginning of the twenty-first century. According to PrefabNZ (2018b) 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 two-dimensional (2D) prefabricated units that do not enclose usable spaces (Bertram et al. 2019). Components are small-scale items assembled off-site such as structural components. Panels refer to planar units that include windows, doors, and integrated services. Volume, hybrid, and complete buildings are three-dimensional (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 on-site (Kennerley 2019; PrefabNZ 2018b).

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 early stage decision-making, detail optimization, 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; and minimizes design errors and discrepancies between the design and final products and enhances mass customization (Mostafa et al. 2020; Singh et al. 2015).

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)]. The NZBC is part of Building Regulations and stipulates 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 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). NZBC is a performance-based code and sets out 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 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 2018b). 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. The evidence of compliance is generally provided in the form of design drawings, calculations, and supporting documentation. For building projects involving OSM, both off- and on-site works must be included in the building consent application. In addition to the 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 subcontractors 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, in which standardized 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, and 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 nonregulatory 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, and contractual) provisions are all conventionally conveyed in natural language subject to human interpretation. The inevitable variations in the interpretation of normative provisions among different people are a common problem. Although the official interpretation of NZBC in the form of a handbook is available, there are still gray 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 nonstandard terminologies when assessing compliance of a given design (İlal and Günaydın 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 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.

Adoption of ACC Technologies

Some of the earlier ACC implementations include Construction and Real Estate Networks (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 since government agencies as well as industry stakeholders were involved in achieving digitalization of the building plan submission and the checking and approval processes (Goh 2007). Unfortunately, it has not been fully utilized for various reasons. DesignCheck aimed to automate the compliance checking process with the Australian accessibility building code in the early 2000s, 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 twentieth century has been summarized 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. 2015, 2016; Park et al. 2016; Preidel and Borrmann 2015, 2016, 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, 2017, 2019). Additionally, although most ACC approaches rely heavily on BIM data as input (Costin et al. 2018), a number of construction projects, especially in developing countries, still use 2D drawings. It was observed that there are efforts trying to extract essential information from 2D drawings and establish 3D semantic understanding of the construction project (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 Automated Compliance Audit of Building Information Models (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 noncompliance (Lee 2021). This is further facilitated by a global transition from paper-based documents to digital data [e.g., Computer aided design (CAD) drawings, BIMs, and digital documents] for checking and approving designs online. For example, the Korean government has funded the development of a BIM-based electronic-submission system to support their national building permitting processes (Kim et al. 2020). The local governments in China have been collaborating with technology firms to develop and online systems for checking building designs against building codes (Wang et al. 2021). Similar attempts have been reported in Norway and Singapore (Hjelseth 2015b). ACC has applications in all stages of a project life cycle [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 2015a; 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) summarized that ACC development has focused on "addressing challenges in sharing digital architectural and engineering design information, formalizing normative provisions as computable rules, and methods of processing them for compliance." Despite the technology development, literature (Lee et al. 2003; Tornatzky et al. 1990) has revealed factors such as human perception and policies significantly contribute to any successful adoption of new technology. A recent survey study by Beach et al. (2020) ascertained a set

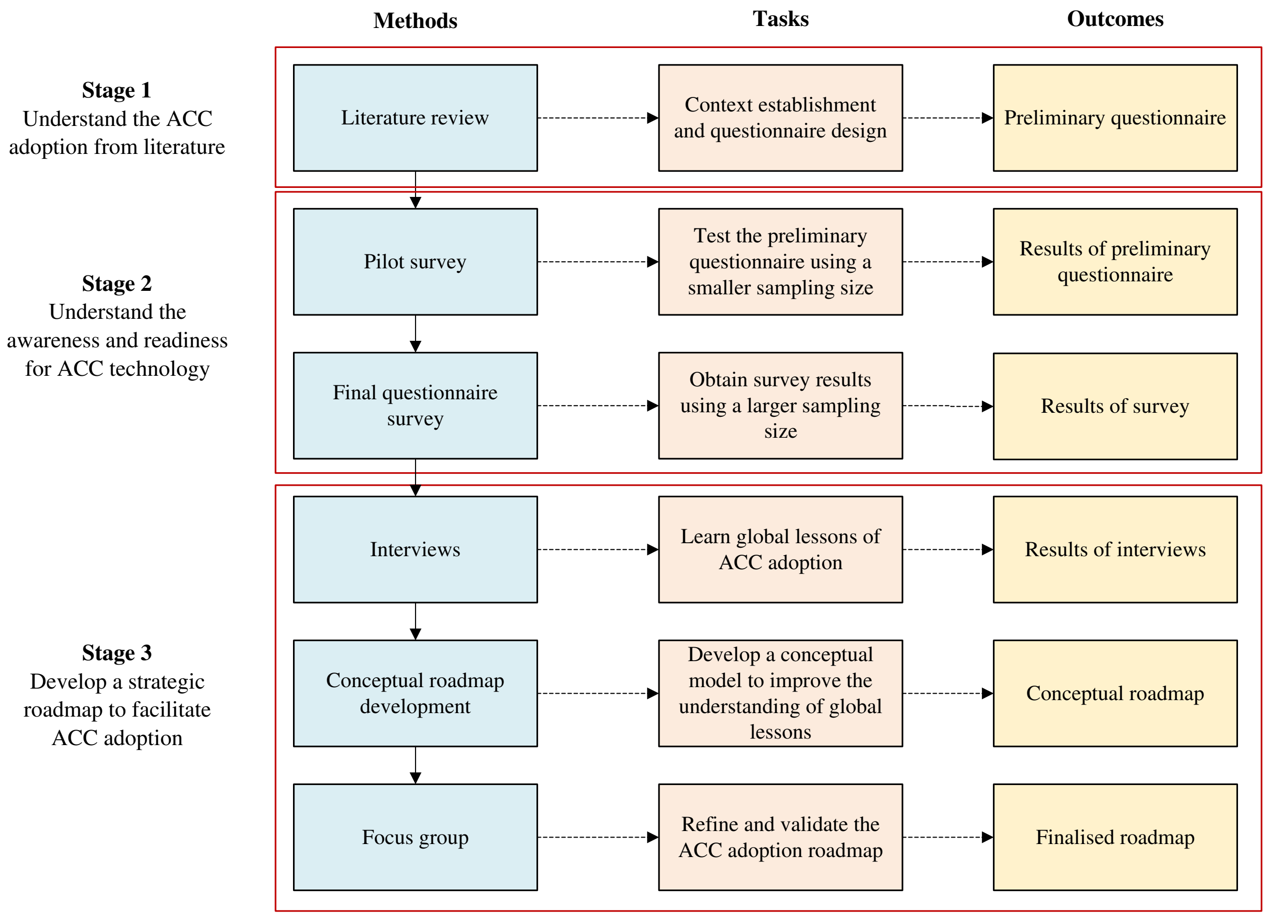

Fig. 1. The research process flow.

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 United Kingdom (UK) context and was limited by only surveying industry professionals who might not be familiar with ACC. This paper aims to narrow this 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 toward wider ACC adoption for NZ OSM industry.

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 Fig. 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 semistructured and consisted of a total of 22 questions in four sections. Section "Introduction" aimed to collect the participants' personal information regarding their specialization and experience with OSM projects. Section "Background and Literature Review" 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 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 using. Section "Research Design and Methods" was designed to answer RQ1, which investigated the current state of the BIM uptake in the NZ OSM industry because 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 BIM use in OSM projects. Section "Research Findings" 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 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 code and nonregulatory requirements, or assessing OSM projects against

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compliance requirements. Since not all respondents were expected to have 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 the questions they had the confidence to answer. Selectable options were summarized from the comprehensive literature review. For example, in Section "Introduction," the selectable options for the question "What type(s) of OSM are included in your company's business scope?" were supported by the "Capacity and Capability Report" of PrefabNZ (2018a). In Section "Research Design and Methods," the selective options for the question "What do you think are the most critical barriers that limit your adoption of BIM in OSM projects?" were summarized from Ahmed (2018), BAC (2019a, b), Ghaffarianhoseini et al. (2017), Pezeshki and Ivari (2018), Sun et al. (2017), and 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.

Stage 2: Understanding the Awareness and Readiness for ACC Technology

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

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; and (2) they are OSM professionals who also have good knowledge in digital design and construction (e.g., BIM, ACC). A total of 160 OSM professionals from Off-siteNZ, a professional OSM association in NZ, were invited by email for the questionnaire survey and a total of 45 respondents completed the survey. The experience, roles, and backgrounds of the respondents had a reasonably even distribution, as shown in Fig. 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, subcontractors, and builders; and 2% were real estate agents. After removing one response from a real estate agent, 44 valid responses remained with a valid response rate of 27.5%. This 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 10 times the population of NZ). Therefore, the sample size was considered satisfactory for the analysis.

The survey results were analyzed using the SPSS Statistics version 27.0 software (IBM 2021) and displayed as tables or charts. Nominal data obtained from multiple-choice and checkbox questions were analyzed 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 in which the qualitative answers had very clear categories, semiquantitative analysis was performed to interpret the responses. The summary of the qualitative responses provides supportive evidence for the quantitative results.

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 transfer evidence-based knowledge and experience to NZ to develop a strategic ACC

Table 1. Interviewee profile (survey study)

Interviewee No.	Position	Industry segment	Area of expertise
1A[a]	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[a]	Director	Engineering consultancy	National expert with >15 years of experience as civil/structural engineer
1F[a]	Director	Manufacturer	International and national expert in NZBC and OSM. Held responsibilities for delivering many large OSM projects in NZ
1G	Principal urban planner	BCA	National leading expert and practitioner in NZBC relating to town planning
1H[a]	BCA officer	BCA	National expert in NZBC and BIM, with nearly 10 years of experience in assessing building consent applications

[a]Interviewees that also attended the focus group.

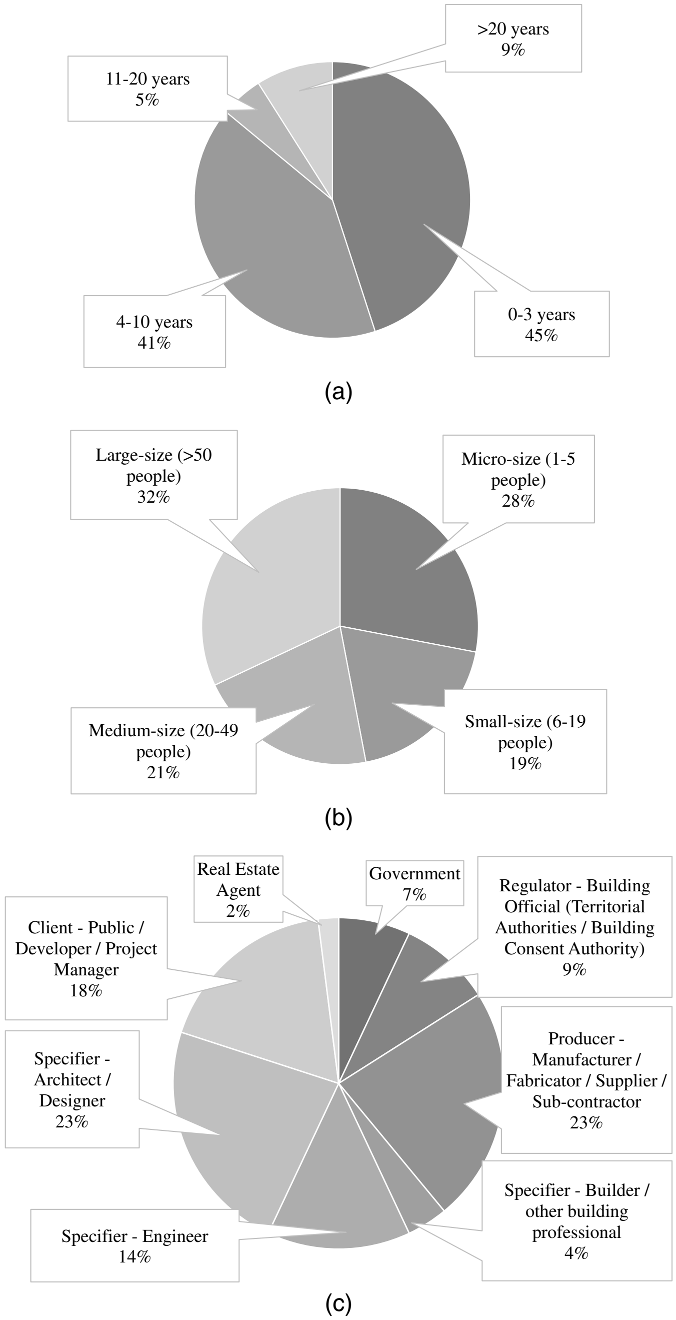

Fig. 2. Respondents' profile: (a) number of years of experience in the NZ OSM industry; (b) approximate sizes of their companies; and (c) roles in OSM projects.

adoption roadmap for the OSM industry, including (1) interviews, (2) conceptual roadmap development, and (3) focus groups (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) experts should have direct experience in the development or testing of at least a functional ACC prototype system that can fully or partly automate the regulatory compliance processes; (2) experts should have real ACC adoption experience (e.g., the ACC system was tested in a pilot project); and (3) ACC adoption experience shared by the experts must have the involvement of multiple key stakeholders. A total of 16 individual interviews (each lasting around 1 h) was conducted through video conference with ACC experts from Australia, China, Denmark, Netherlands, NZ, Norway, Singapore, South Korea, and the United Kingdom. The profile of interviewees and key interview questions can be found in Tables 2 and 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 were suggested. These interviews were grouped based on respondents' countries because each country has its unique characteristics in terms of policy, building code, regulation system, building typology, building consent processes, stakeholder requirements, and so forth. The data for each country was initially studied separately such that the data can 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 analyzed and refined, a cross-country analysis took place following the recommendations of Miles et al. (2014).

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, nine industry experts in the positions of BCA officer, design directors, project manager, and BIM specialist attended a FG. Five out of the nine experts participated in interviews in previous stages, and the rest of the experts were identified and invited for their good knowledge in BIM, OSM, and NZBC. The FG was held online through video conference for around 3 h and focused on (1) finding missing and inappropriate items, and (2) improving time-sequential relationship of suggested actions to finalize the roadmap. The experts were also asked to comment if there was any customization needed to the roadmap for 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 because 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 then emailed to all FG experts who were asked to check the roadmap and confirm no further changes were needed.

Research Findings

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. A total of 57% of respondents had no or very limited experience in using BIM for OSM design. But 36% chose the score of seven or higher, showing that BIM had been integrated into their OSM design process and business.

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 the 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 standardization expert
2K	Standard expert	NZ	National leading standardization expert
2L[a]	Academic researcher	NZ	International leading expert with >30 years of ACC research experience
2M	OSM expert	UK	OSM expert who had project experience in both the 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

Note: Two interviews involved two interviewees (2G/2H and 2J/2K) each time.
[a]Interviewee that also attended the focus group.

Table 3. Key interview questions (roadmap development)

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?

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).

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 seven, indicating a distinct trend of a high level of recognition to the benefits of BIM. Similarly, good awareness of BIM use in future OSM projects such as 3D visualization 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, where 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 and 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 recognized by the OSM industry. A total of 65% of respondents only scored two or less (median is only 1 out of 10) when asked the questions of how large a 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 explained 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 started 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

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

Survey question	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	9	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

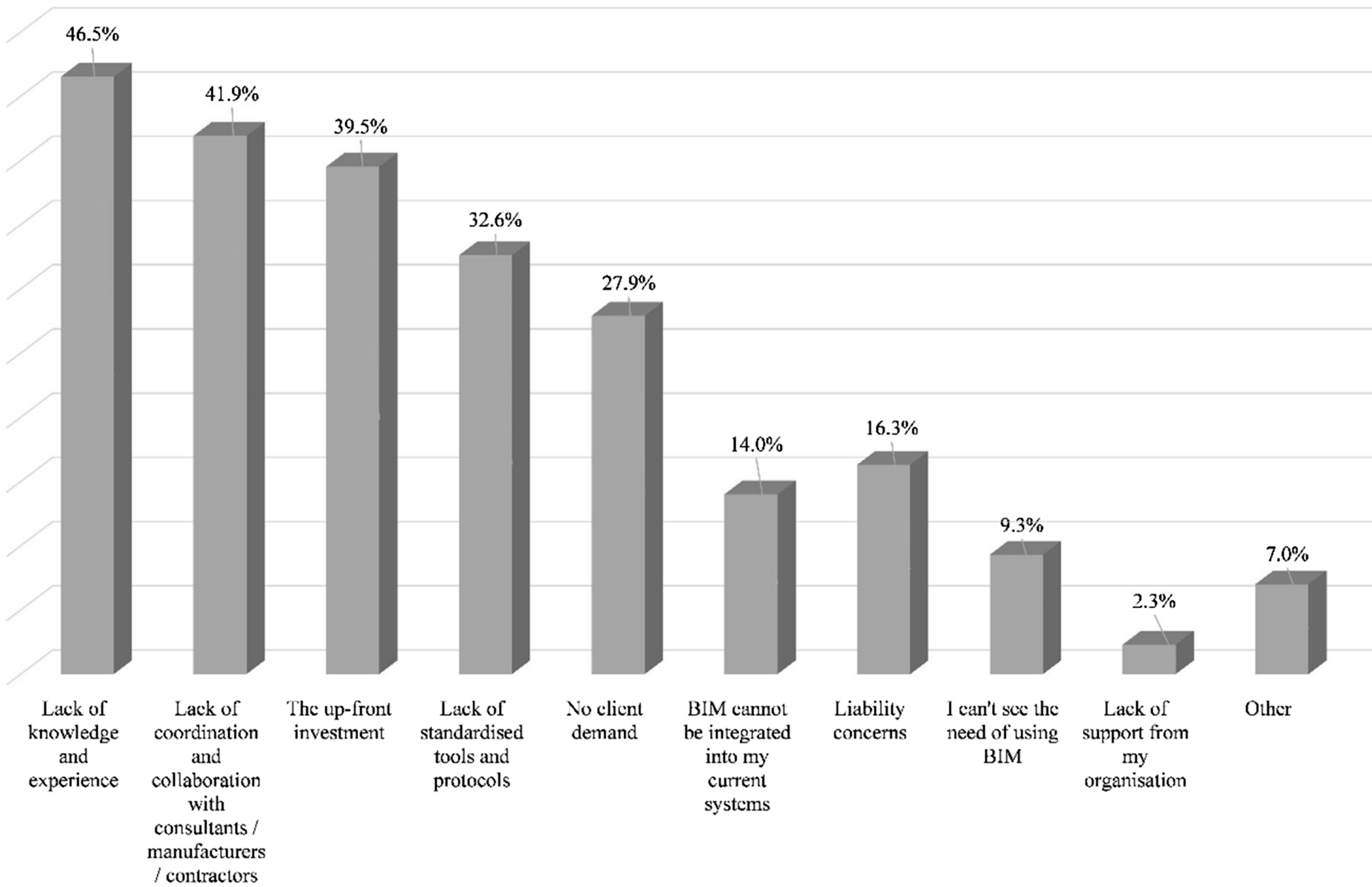

Fig. 3. Results for question regarding the most critical barriers limiting BIM adoption in the NZ OSM industry.

BIM-based building code compliance in NZ that can 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.

Fig. 3 shows the survey respondents' opinions on critical barriers to BIM adoption in 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 standardized 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 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 data set 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 using BIM is necessary.

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 cope 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 automate or semiautomate the building code compliance processes. As an alternative, a commonly used industry practice to reduce the risks 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 can improve the existing building code compliance process toward the approval of a building consent application (Table 5).

Table 5. Received suggestions that can improve the existing building code compliance process toward the approval of a building consent application

Number	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 organizations to avoid unnecessary iterations and demonstrate a better integrated OSM building product
3	Improve the consistency in understanding the building code among BCAs

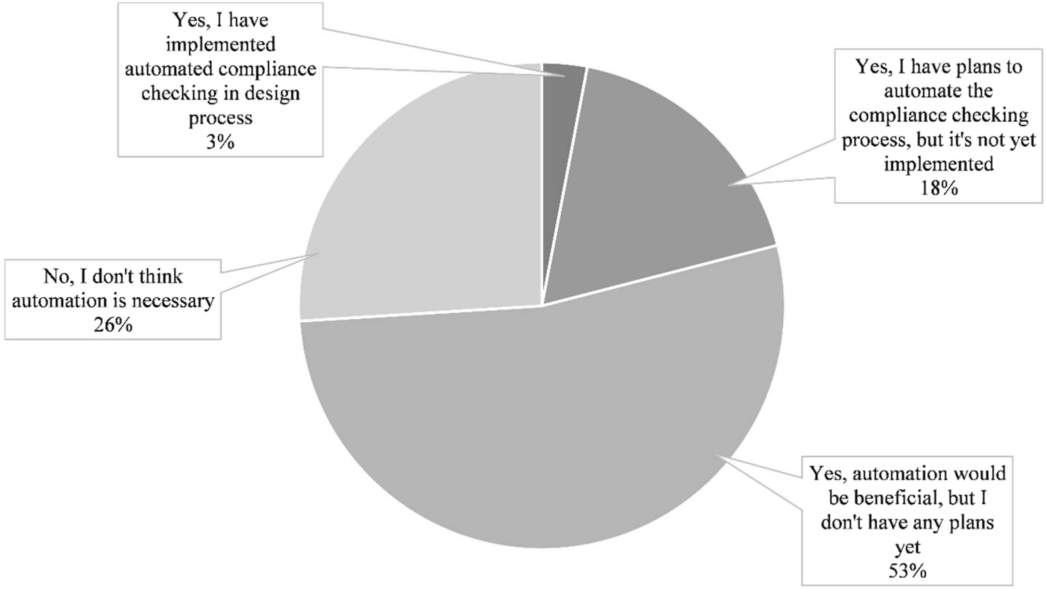

Fig. 4. Results for question regarding the demand and plans on automating the compliance checking process.

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

Number	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	Synchronized design changes and comments between designers and building consent specialists can reduce a significant amount of paperwork and avoid ambiguities in communication.
3	A set of minimum data requirements and a required compliance information list will facilitate standardizing the compliance checking process, as OSM often involves design for manufacture and assembly 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.

Although ACC for OSM projects has not started, the importance of having such technologies is widely recognized by the survey respondents and interviewees. As shown in Fig. 4, the majority of the respondents (74%) have implemented ACC in their design process, expressed their interest in ACC, or 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).

The level of perceived benefits of potentially adopting ACC technology for OSM projects, businesses, and industry were evaluated. As shown in Fig. 5, 86% of respondents suggested that ACC technology would bring substantial benefits to OSM projects and improve quality, cost control, and delivery; 31 respondents (74%) agreed that automating the building code compliance process would bring tangible and intangible benefits to their organizations or companies; and 30 respondents (72%) held a view that if such automation technologies existed, it would expedite the broader

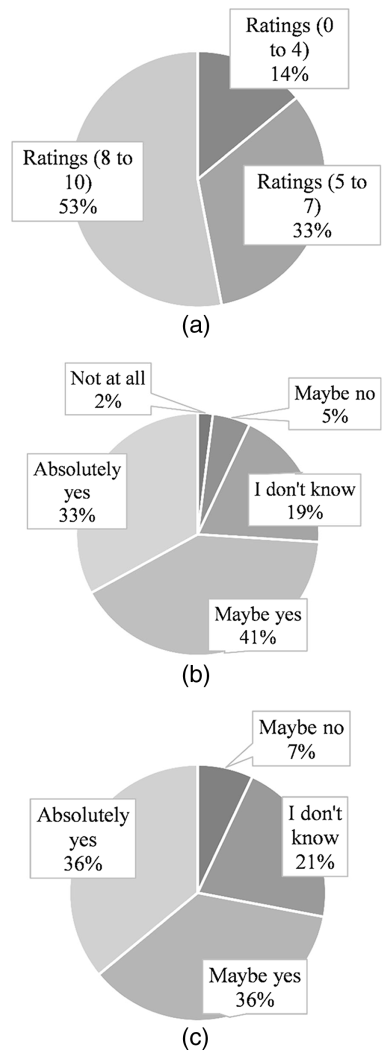

Fig. 5. Survey results regarding the perceived benefit of the automated building code compliance technology for (a) improving OSM quality, cost control, and delivery; (b) the respondent's organizations or companies; and (c) facilitating greater adoption.

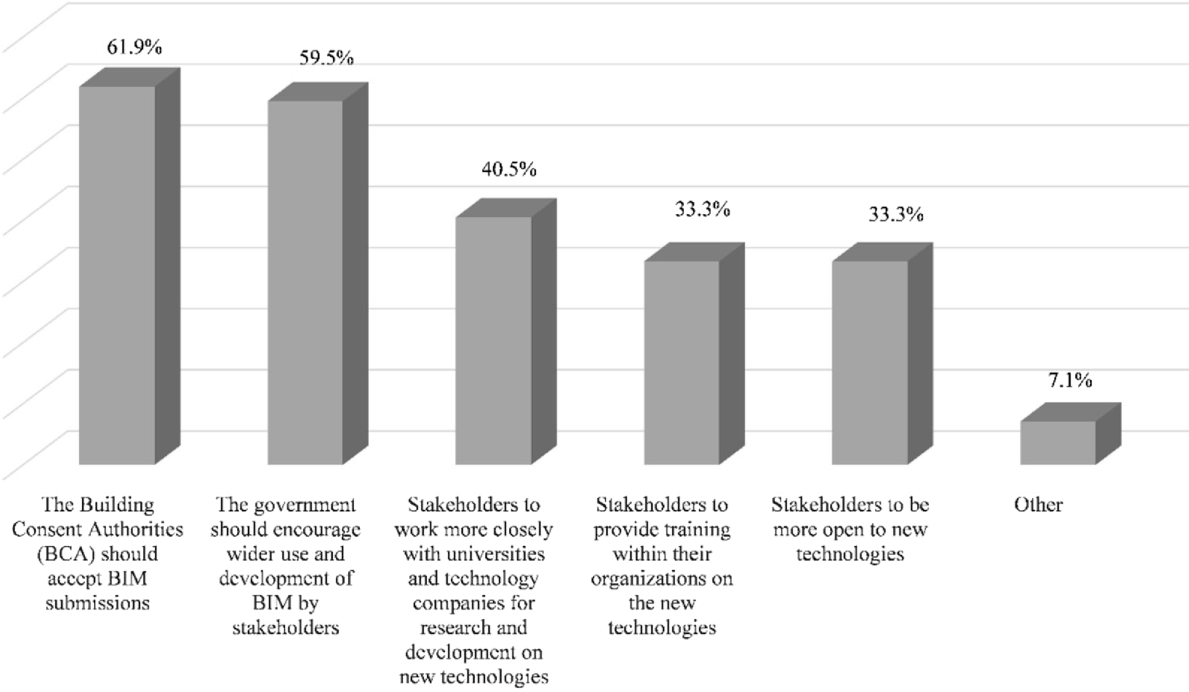

Fig. 6. Critical barriers to ACC technology adoption.

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.

As to the critical barriers that prevent ACC adoption (Fig. 6), 61.9% of survey respondents suggested that BCA has not started 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 recognize, accept, and integrate ACC technologies into existing work processes, and 33.3% of respondents believed training and education are critical for professionals to upgrade their knowledge and have the right skills to use ACC.

A Roadmap to Facilitate the Adoption of ACC for NZ OSM Industry

The final roadmap is presented in Fig. 7, describing key actions that can facilitate wider ACC adoption within NZ OSM industry in three contexts, according to the technology-organization-environment (TOE) framework (Tornatzky et al. 1990). The *organization* in this study refers to the NZ OSM industry, *technology* includes actions that are relevant to ACC-related technologies, and *environment* consists of regulatory environment and external support by the government. A total of 30 key actions were identified. Their description and justification can be found in Tables 7–9.

The timeline of the proposed roadmap is divided into four stages: (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 in which 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 customized ACC solutions to 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 noncertified materials and check if the products meet regulatory requirements by local councils. The designers may also take advantage of ACC to check tolerances of erection of prefabricated components and whether the selection of a specific type of OSM house for a site in Auckland, the largest city in NZ, 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.

Discussion

Contribution to Knowledge

First, 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 (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

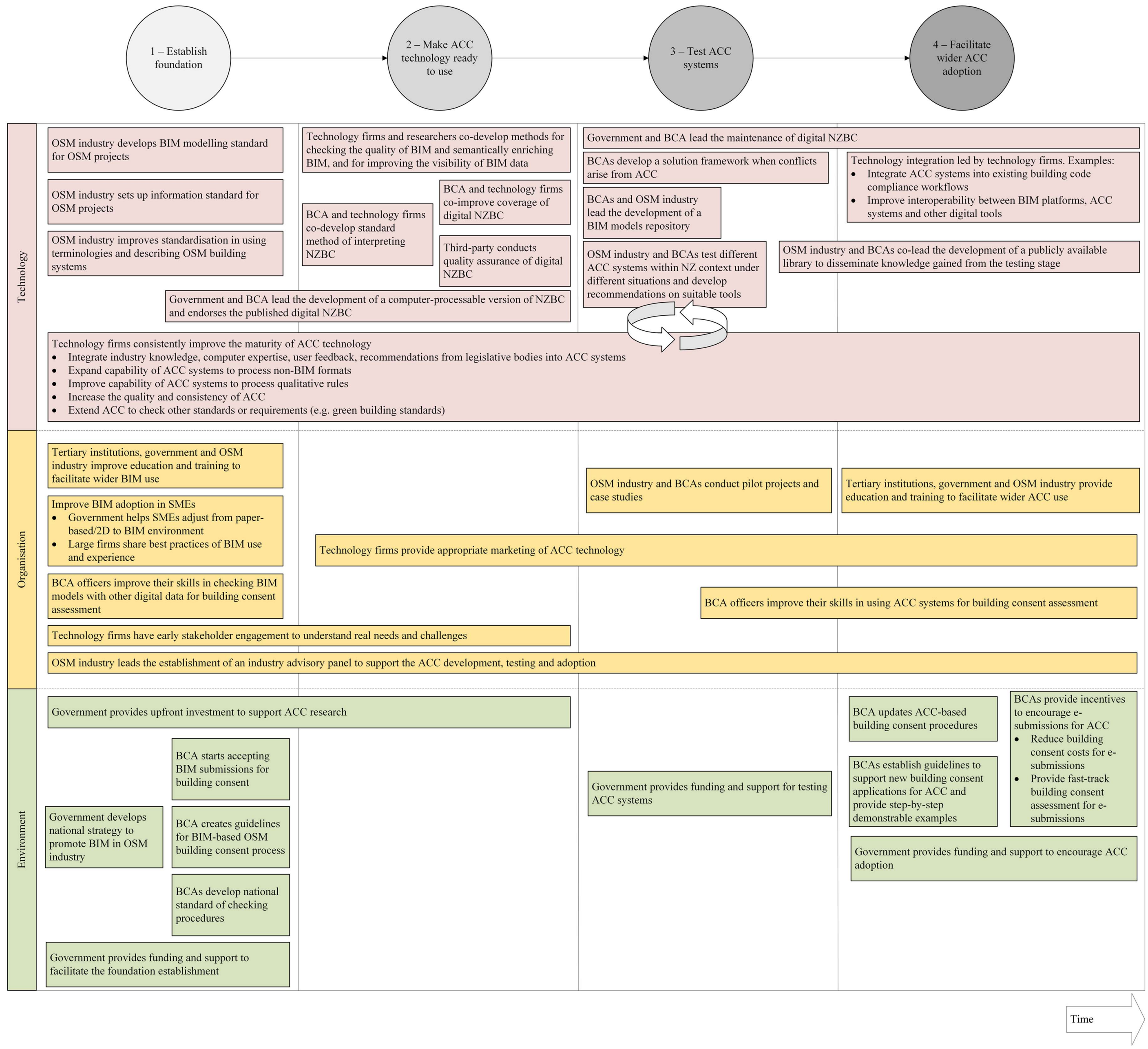

Fig. 7. A roadmap to facilitate the adoption of ACC in NZ OSM industry.

PrefabNZ (2018a) "Capacity and Capability Report," 59% OSM companies in NZ are small businesses with less than 20 employees. Improving the BIM awareness and skills of SMEs may significantly increase the BIM adoption rate in NZ OSM industry since a study by Hong et al. (2019) suggested SMEs are generally much slower in BIM uptake than large firms. Relevant experience and lessons might be learned from other developed countries such as the 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) BCAs have not formally started to accept and process BIM submissions for building consent process, and (3) no proven case studies exist. A number of challenges limiting the BIM implementation in NZ were received (Fig. 3) and the top three challenges included (1) lack of knowledge and experience, (2) lack of coordination and collaboration with consultants, manufacturers, and contractors, and (3) up-front investment.

Second, this paper explored the NZ OSM industry's awareness of and demand for ACC systems (RQ2). The findings confirm that automating the building code compliance is in demand (Fig. 4), especially to support the building consent processes. ACC has been considered to be a task for designers and BCAs; the potential value of the wider application of ACC to the life cycle of OSM projects was ignored by most survey participants. Compared to 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, simultaneous running of logistics, and coordination of both off- and on-site work. There is a need to further develop and employ ACC solutions to check both the mandatory NZBC and other nonregulatory compliance requirements (e.g., certification

Table 7. Roadmap: technology actions

No.	Stage(s)	Suggested action	Description and justification
1	1	OSM industry develops BIM modeling 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	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 minimize modeling efforts and reduce confusion, making ACC easier to be accepted by end users.
3	1	OSM industry improves standardization 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 off-site 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	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. 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). In the future, there is also a strong need to convert the guidelines and nonregulatory compliance documents for OSM projects [e.g., (Auckland Council 2020; James et al. 2017; PrefabNZ 2018b)] into machine-readable forms for ACC. For example, the preagreed product, erection, and interfacing tolerances can be checked in BIM-based design so that both off- and on-site teams can have confidence to build the project as designed.
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 codevelop 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 visualization and visibility (Liu et al. 2016) might be further developed to make the BIM data more machine-processable for ACC purpose.
7	2	BCA and technology firms codevelop 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 coimprove the coverage of NZBC	The challenging aspect of checking qualitative normative provisions needs to be addressed.
9	2	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/BCA leads the maintenance of digital NZBC	Since building code is updated and revised regularly, the digital version of NZBC needs to be updated accordingly.

Table 7. (*Continued.*)

No.	Stage(s)	Suggested action	Description and justification
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 colead 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: organization 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 subcontractors, 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 electronic 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.
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 get 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.

of materials, zoning requirements, manufacturing and erection tolerances, site restrictions, and 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 up-front investment, big learning curves, 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

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 the 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 already have been observed 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, in which 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 up-front 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	The funding and support from government can help industry to 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.
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 electronic submissions for ACC	For instance, electronic 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.

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., Common data environment (CDE)], (2) ACC systems can synchronize design changes and comments between designers and BCAs, and (3) a set of minimum data requirements should be provided to the practitioners for ACC purpose. Additionally, an important finding is that BCA and other government departments can play an important role in the process of transforming the OSM industry to adopt ACC technologies through proper policies, programs, and guidelines, which may significantly shorten the building consent processes.

Third, in response to RQ3, a high-level roadmap (Fig. 7) was proposed to describe key actions in the contexts of technology, organization 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, customize it to be suitable for 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 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.

Practical Implications

A number of practical implications can be drawn for the OSM industry in NZ. First, 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 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. Second, one major driver of adopting ACC systems for 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 moving slowly to take up this change for various reasons. At this stage, BCA officers across NZ have different levels of understanding and technical capabilities 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, 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.

Limitations

Two limitations exist in this study. First, the sampling size of the first stage survey was relatively small. This was partly because NZ has a small OSM industry, which led to the difficulty in finding 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 the 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 and manufacturers) and BCA. To enrich the closed questionnaire responses, add qualitative insights, and validate the collected data set, eight semistructured interviews were used. Second, this study did not consider variables such as cultural and social factors, which might be significant factors to individual OSM companies for considering ACC adoption.

Conclusion and Recommendation for Future Research

Given the growing demand for integrating ACC into OSM projects, this paper first 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 NZ OSM industry. The results found that professionals have seen 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, organization, and environment can lead to broader ACC adoption in 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 organization 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 indicated 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 electronic submissions and ACC-based building consent assessment. Overall, this study complemented previous technology-focused efforts and enhanced our understanding on nontechnology 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.

Data Availability Statement

All data that support the findings of this study are available from the corresponding author upon reasonable request.

Acknowledgments

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References

Abd Samad, S., A. N. Harun, M. N. M. Nawi, and N. A. Haron. 2018. "The potential use of BIM through an electronic submission: A preliminary study." *Malaysian Constr. Res. J.* 3 (1): 82–96.

Ahmed, S. 2018. "Barriers to implementation of building information modeling (BIM) to the construction industry: A review." *J. Civ. Eng. Constr.* 7 (2): 107–113. https://doi.org/10.32732/jcec.2018.7.2.107.

Aksenova, G., A. Kiviniemi, T. Kocaturk, and A. Lejeune. 2019. "From Finnish AEC knowledge ecosystem to business ecosystem: Lessons learned from the national deployment of BIM." *Construct. Manage. Econ.* 37 (6): 317–335. https://doi.org/10.1080/01446193.2018.1481985.

Amor, R., and J. Dimyadi. 2021. "The promise of automated compliance checking." *Dev. Built Environ.* 5 (Mar): 100039. https://doi.org/10.1016/j.dibe.2020.100039.

Arashpour, M., Y. Bai, V. Kamat, R. Hosseini, and I. Martek. 2018. "Project production flows in off-site prefabrication: BIM-enabled railway infrastructure." In *Proc., 35th Int. Symp. on Automation and Robotics in Construction (ISARC)*, 80–87. Berlin, Germany: International Association for Automation and Robotics in Construction.

Auckland Council. 2016. *Auckland unitary plan*. Auckland, New Zealand: Auckland Council.

Auckland Council. 2020. *Manufactured modular component guidance*. Auckland, New Zealand: Auckland Council.

(BAC) BIM Acceleration Committee. 2019a. *BIM in New Zealand—An industry-wide view 2019*. Wellington, New Zealand: Building Research Association of New Zealand.

(BAC) BIM Acceleration Committee. 2019b. *The New Zealand BIM handbook—A guide to enabling BIM on built assets*. Wellington, New Zealand: Building Research Association of New Zealand.

Beach, T. H., J.-L. Hippolyte, and Y. Rezgui. 2020. "Towards the adoption of automated regulatory compliance checking in the built environment." *Autom. Constr.* 118 (Oct): 103285. https://doi.org/10.1016/j.autcon.2020.103285.

Beach, T. H., T. Kasim, H. Li, N. Nisbet, and Y. Rezgui. 2013. "Towards automated compliance checking in the construction industry." In *Proc., Int. Conf. on Database and Expert Systems Applications*, 366–380. Berlin: Springer.

Beach, T. H., Y. Rezgui, H. Li, and T. Kasim. 2015. "A rule-based semantic approach for automated regulatory compliance in the construction sector." *Expert Syst. Appl.* 42 (12): 5219–5231. https://doi.org/10.1016/j.eswa.2015.02.029.

Bertram, N., S. Fuchs, J. Mischke, R. Palter, G. Strube, and J. Woetzel. 2019. *Modular construction: From projects to products*. New York: McKinsey & Company.

Bloch, T., and R. Sacks. 2018. "Comparing machine learning and rule-based inferencing for semantic enrichment of BIM models." *Autom. Constr.* 91 (Jul): 256–272. https://doi.org/10.1016/j.autcon.2018.03.018.

Bonenberg, W., X. Wei, and M. Zhou. 2018. "BIM in prefabrication and modular building." In *Proc., Int. Conf. on Applied Human Factors and Ergonomics*, 100–110. Orlando, FL: Springer.

Bouzidi, K. R., B. Fies, C. Faron-Zucker, A. Zarli, and N. L. Thanh. 2012. "Semantic web approach to ease regulation compliance checking in construction industry." *Future Internet* 4 (3): 830–851. https://doi.org/10.3390/fi4030830.

Boyd, N., M. M. Khalfan, and T. Maqsood. 2013. "Off-site construction of apartment buildings." *J. Archit. Eng.* 19 (1): 51–57. https://doi.org/10.1061/(ASCE)AE.1943-5568.0000091.

Bus, N., A. Roxin, G. Picinbono, and M. Fahad. 2018. "Towards french smart building code: Compliance checking based on semantic rules." In *Proc., 6th Linked Data in Architecture and Construction Workshop*, edited by M. Poveda-Villalón, P. Pauwels, and A. Roxin, 6–15. Aachen, Germany: CEUR-WS Team.

Choi, J., and I. Kim. 2008. "An approach to share architectural drawing information and document information for automated code checking system." *Tsinghua Sci. Technol.* 13 (S1): 171–178. https://doi.org/10.1016/S1007-0214(08)70145-7.

Choi, J., and I. Kim. 2013. "Development of check-list for BIM based architectural design quality check." *Korean J. Comput. Des. Eng.* 18 (3): 177–188. https://doi.org/10.7315/CADCAM.2013.177.

Ciribini, A., S. M. Ventura, and M. Paneroni. 2016. "Implementation of an interoperable process to optimise design and construction phases of a residential building: A BIM pilot project." *Autom. Constr.* 71 (Nov): 62–73. https://doi.org/10.1016/j.autcon.2016.03.005.

Costin, A., A. Adibfar, H. Hu, and S. S. Chen. 2018. "Building information modeling (BIM) for transportation infrastructure–Literature review, applications, challenges, and recommendations." *Autom. Constr.* 94 (Oct): 257–281. https://doi.org/10.1016/j.autcon.2018.07.001.

Creswell, J. W. 2009. *Research design: Qualitative, quantitative and mixed methods approaches*. Thousand Oaks, CA: SAGE.

Dimyadi, J., and R. Amor. 2013. "Automated building code compliance checking. Where is it at?" In *Proc., CIB World Building Congress 2013 and Architectural Management & Integrated Design and Delivery Solutions*, 172–185. Brisbane, Australia: Queensland Univ. of Technology.

Dimyadi, J., and R. Amor. 2017. "Automating conventional compliance audit processes." In *Proc., Int. Conf. on Product Lifecycle Management*, 324–334. Seville, Spain: Springer.

Dimyadi, J., S. Fernando, K. Davies, and R. Amor. 2020. "Computerising the New Zealand building code for automated compliance audit." In *Proc., 6th New Zealand Built Environment Research Symp.*, 39–46. Auckland, New Zealand: Massey Univ.

Dimyadi, J., W. Solihin, C. Eastman, and R. Amor. 2016. "Integrating the BIM rule language into compliant design audit processes." In *Proc., 33rd Int. Conf. of CIB W78*, 1–10. Delft, Netherlands: International Council for Research and Innovation in Building and Construction.

Dimyadi, J., G. Thomas, and R. Amor. 2017. "Enabling automated compliance audit of architectural designs." In *Proc., 51st Int. Conf. of the Architectural Science Association (ANZAScA),* edited by M. A. Schnabel, 387–396. Sydney, Australia: Architectural Science Association.

Ding, L., R. Drogemuller, M. Rosenman, D. Marchant, and J. Gero. 2006. "Automating code checking for building designs-DesignCheck." In *Clients driving construction innovation: Moving ideas into practice*, edited by K. Brown, K. Hampson, and P. Brandon, 113–126. Brisbane, Australia: Cooperative Research Centre for Construction Innovation.

Doan, D. T., A. Ghaffarianhoseini, N. Naismith, A. Ghaffarianhoseini, T. Zhang, and J. Tookey. 2019. "Examining green star certification uptake and its relationship with building information modelling (BIM) adoption in New Zealand." *J. Environ. Manage.* 250 (Nov): 109508. https://doi.org/10.1016/j.jenvman.2019.109508.

Eastman, C., J.-M. Lee, Y.-S. Jeong, and J.-K. Lee. 2009. "Automatic rule-based checking of building designs." *Autom. Constr.* 18 (8): 1011–1033. https://doi.org/10.1016/j.autcon.2009.07.002.

Eastman, C., P. Teicholz, R. Sacks, and K. Liston. 2011. *BIM handbook: A guide to building information modeling for owners, managers, designers, engineers and contractors*. Hoboken, NJ: Wiley.

Elyan, E., L. Jamieson, and A. Ali-Gombe. 2020. "Deep learning for symbols detection and classification in engineering drawings." *Neural Networks* 129 (Sep): 91–102. https://doi.org/10.1016/j.neunet.2020.05.025.

Etikan, I., S. A. Musa, and R. S. Alkassim. 2016. "Comparison of convenience sampling and purposive sampling." *Am. J. Theor. Appl. Stat.* 5 (1): 1–4. https://doi.org/10.11648/j.ajtas.20160501.11.

Gbadamosi, A.-Q., L. Oyedele, A.-M. Mahamadu, H. Kusimo, M. Bilal, J. M. Davila Delgado, and N. Muhammed-Yakubu. 2020. "Big data for design options repository: Towards a DFMA approach for offsite construction." *Autom. Constr.* 120 (Dec): 103388. https://doi.org/10.1016/j.autcon.2020.103388.

Ghaffarianhoseini, A., J. Tookey, A. Ghaffarianhoseini, N. Naismith, S. Azhar, O. Efimova, and K. Raahemifar. 2017. "Building information modelling (BIM) uptake: Clear benefits, understanding its implementation, risks and challenges." *Renewable Sustainable Energy Rev.* 75 (Aug): 1046–1053. https://doi.org/10.1016/j.rser.2016.11.083.

Goh, B.-H. 2007. "E-government for construction: The case of Singapore's CORENET project." In *Proc., of Research and Practical Issues of Enterprise Information Systems II*, 327–336. New York: Springer.

Goodier, C., and A. Gibb. 2007. "Future opportunities for offsite in the UK." *Construct. Manage. Econ.* 25 (6): 585–595. https://doi.org/10.1080/01446190601071821.

GSA. 2015. *GSA BIM guide 02—Spatial program validation*. Washington, DC: US General Services Administration.

Hanna, A. S., G. Mikhail, and K. A. Iskandar. 2017. "State of prefab practice in the electrical construction industry: Qualitative assessment." *J. Constr. Eng. Manage.* 143 (2): 04016097. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001236.

Harpe, S. E. 2015. "How to analyze Likert and other rating scale data." *Curr. Pharm. Teach. Learn.* 7 (6): 836–850. https://doi.org/10.1016/j.cptl.2015.08.001.

Hjelseth, E. 2015a. "BIM-based model checking (BMC)." In *Building information modeling: Applications and practices*, edited by R. Issa and S. Olbina, 33–61. Reston, VA: ASCE.

Hjelseth, E. 2015b. "Public BIM-based model checking solutions: Lessons learned from Singapore and Norway." In *Building information modelling (BIM) in design, construction and operations*, edited by L. Mahdjoubi, C. A. Brebbia, and R. Laing, 421–436. Southampton, UK: Wessex Institute of Technology Press.

Hong, Y., A. W. Hammad, S. Sepasgozar, and A. Akbarnezhad. 2019. "BIM adoption model for small and medium construction organisations in Australia." *Eng. Constr. Archit. Manage.* 26 (2): 154–183. https://doi.org/10.1108/ECAM-04-2017-0064.

Hosseini, M. R., S. Banihashemi, N. Chileshe, M. O. Namzadi, C. Udeaja, R. Rameezdeen, and T. McCuen. 2016. "BIM adoption within Australian small and medium-sized enterprises (SMEs): An innovation diffusion model." *Constr. Econ. Build.* 16 (3): 71–86. https://doi.org/10.5130/ajceb.v16i3.5159.

IBM. 2021. "SPSS statistics." Accessed August 7, 2021. https://www.ibm.com/analytics/spss-statistics-software.

İlal, S. M., and H. M. Günaydın. 2017. "Computer representation of building codes for automated compliance checking." *Autom. Constr.* 82 (Oct): 43–58. https://doi.org/10.1016/j.autcon.2017.06.018.

James, M., B. Yu, and B. Martin. 2017. *Handbook for the design of modular structures*. Melbourne, Australia: Monash University Press.

Javid, M. A., N. Ali, M. Abdullah, T. Campisi, S. A. H. Shah, and S. Suparp. 2022. "Analysis of driver's socioeconomic characteristics relating to speeding behavior and crash involvement: A case study in Lahore." *Infrastructures* 7 (2): 18. https://doi.org/10.3390/infrastructures7020018.

Jiang, S., Z. Wu, B. Zhang, and H. S. Cha. 2019. "Combined MvdXML and semantic technologies for green construction code checking." *Appl. Sci.* 9 (7): 1463. https://doi.org/10.3390/app9071463.

Kasim, T., H. Li, Y. Rezgui, and T. Beach. 2013. "Automated sustainability compliance checking process: Proof of concept." In *Proc., 13th Int. Conf.*

on Construction Applications of Virtual Reality, 30–31. Middlesbrough, UK: Teesside Univ.

Kennerley, T. 2019. *Planning barriers for prefabricated housing*. Porirua, New Zealand: BRANZ.

Khemlani, L. 2005. "CORENET e-PlanCheck: Singapore's automated code checking system." *AECbytes*. Accessed 15 November, 2021. https://www.aecbytes.com/feature/2005/CORENETePlanCheck.html.

Kim, I., J. Choi, E. A. L. Teo, and H. Sun. 2020. "Development of K-BIM e-Submission prototypical system for the openBIM-based building permit framework." *J. Civ. Eng. Manage.* 26 (8): 744–756. https://doi.org/10.3846/jcem.2020.13756.

Ko, C.-H., and S.-F. Wang. 2010. "GA-based decision support systems for precast production planning." *Autom. Constr.* 19 (7): 907–916. https://doi.org/10.1016/j.autcon.2010.06.004.

Krijnen, T., and L. Van Berlo. 2016. "Methodologies for requirement checking on building models: A technology overview." In *Proc., 13th Int. Conf. on Design and Decision Support Systems in Architecture and Urban Planning*, 1–11. Eindhoven, Netherlands: Eindhoven Univ. of Technology.

Lam, T. T., L. Mahdjoubi, and J. Mason. 2017. "A framework to assist in the analysis of risks and rewards of adopting BIM for SMEs in the UK." *J. Civ. Eng. Manage.* 23 (6): 740–752. https://doi.org/10.3846/13923730.2017.1281840.

Lee, H., J.-K. Lee, S. Park, and I. Kim. 2016. "Translating building legislation into a computer-executable format for evaluating building permit requirements." *Autom. Constr.* 71 (Nov): 49–61. https://doi.org/10.1016/j.autcon.2016.04.008.

Lee, H. M. 2021. "Assessing information-input standardisation for automated compliance checking efficiency." Master's dissertation, Wellington School of Architecture, Victoria Univ. of Wellington.

Lee, J.-K., C. M. Eastman, and Y. C. Lee. 2015. "Implementation of a BIM domain-specific language for the building environment rule and analysis." *J. Intell. Rob. Syst.* 79 (3–4): 507–522. https://doi.org/10.1007/s10846-014-0117-7.

Lee, Y., K. A. Kozar, and K. R. Larsen. 2003. "The technology acceptance model: Past, present, and future." *Commun. Assoc. Inf. Syst.* 12 (1): 50. https://doi.org/10.17705/1cais.01250.

Li, C. Z., R. Y. Zhong, F. Xue, G. Xu, K. Chen, G. G. Huang, and G. Q. Shen. 2017. "Integrating RFID and BIM technologies for mitigating risks and improving schedule performance of prefabricated house construction." *J. Cleaner Prod.* 165 (Nov): 1048–1062. https://doi.org/10.1016/j.jclepro.2017.07.156.

Lincoln, Y. S., and E. G. Guba. 1985. *Naturalistic inquiry.* Thousand Oaks, CA: SAGE.

Liu, X., N. Xie, K. Tang, and J. Jia. 2016. "Lightweighting for Web3D visualization of large-scale BIM scenes in real-time." *Graphical Models* 88 (Nov): 40–56. https://doi.org/10.1016/j.gmod.2016.06.001.

Lu, Y., Q. Li, Z. Zhou, and Y. Deng. 2015. "Ontology-based knowledge modeling for automated construction safety checking." *Saf. Sci.* 79 (Nov): 11–18. https://doi.org/10.1016/j.ssci.2015.05.008.

Malsane, S., J. Matthews, S. Lockley, P. E. Love, and D. Greenwood. 2015. "Development of an object model for automated compliance checking." *Autom. Constr.* 49 (Jan): 51–58. https://doi.org/10.1016/j.autcon.2014.10.004.

Martins, J. P., and A. Monteiro. 2013. "LicA: A BIM based automated code-checking application for water distribution systems." *Autom. Constr.* 29 (Jan): 12–23. https://doi.org/10.1016/j.autcon.2012.08.008.

MBIE. 2014. *New Zealand building code handbook*. Wellington, New Zealand: Ministry of Business, Innovation & Employment.

MBIE. 2018. *Annual report 2017/18*. Wellington, New Zealand: Ministry of Business, Innovation & Employment.

Miles, M. B., A. M. Huberman, and J. Saldana. 2014. *Qualitative data analysis: A methods sourcebook*. Thousand Oaks, CA: SAGE.

Mostafa, S., K. P. Kim, V. W. Tam, and P. Rahnamayiezekavat. 2020. "Exploring the status, benefits, barriers and opportunities of using BIM for advancing prefabrication practice." *Int. J. Constr. Manage.* 20 (2): 146–156. https://doi.org/10.1080/15623599.2018.1484555.

Nawari, N. O. 2011. "Automating codes conformance in structural domain." In *Proc., 2011 ASCE Int. Workshop on Computing in Civil Engineering*. Reston, VA: ASCE. https://doi.org/10.1061/41182(416)70.

Nawari, N. O. 2012. "BIM standard in off-site construction." *J. Archit. Eng.* 18 (2): 107–113. https://doi.org/10.1061/(asce)ae.1943-5568.0000056.

Nawari, N. O. 2019. "A generalized adaptive framework (GAF) for automating code compliance checking." *Buildings* 9 (4): 86. https://doi.org/10.3390/buildings9040086.

Nguyen, T.-H., and J.-L. Kim. 2011. "Building code compliance checking using BIM technology." In *Proc., 2011 Winter Simulation Conf.*, 3395–3400. Phoenix, Arizona: IEEE.

Palinkas, L. A., S. M. Horwitz, C. A. Green, J. P. Wisdom, N. Duan, and K. Hoagwood. 2015. "Purposeful sampling for qualitative data collection and analysis in mixed method implementation research." *Administration Policy Mental Health* 42 (5): 533–544. https://doi.org/10.1007/s10488-013-0528-y.

Panjehpour, M., and A. A. A. Ali. 2013. "A review of prefab home and relevant issues." *Constructii* 14 (1): 53–60.

Park, S., Y.-C. Lee, and J.-K. Lee. 2016. "Definition of a domain-specific language for Korean building act sentences as an explicit computable form." *J. Inf. Technol. Constr.* 21 (2016): 422–433.

Pezeshki, Z., and S. A. S. Ivari. 2018. "Applications of BIM: A brief review and future outline." *Arch. Comput. Methods Eng.* 25 (2): 273–312. https://doi.org/10.1007/s11831-016-9204-1.

Piroozfar, P., E. R. Farr, A. H. Zadeh, S. T. Inacio, S. Kilgallon, and R. Jin. 2019. "Facilitating building information modelling (BIM) using integrated project delivery (IPD): A UK perspective." *J. Build. Eng.* 26 (Nov): 100907. https://doi.org/10.1016/j.jobe.2019.100907.

PrefabNZ. 2018a. "Capacity and capability report." Accessed August 11, 2021. https://www.prefabnz.com/Downloads/Assets/9759/1/.

PrefabNZ. 2018b. "Good offsite guide." Accessed August 10, 2021. https://www.prefabnz.com/Downloads/Assets/9743/1/PrefabNZ%20Good%20Offsite%20Guide%20FINAL%20(1).pdf.

Preidel, C., and A. Borrmann. 2015. "Automated code compliance checking based on a visual language and building information modeling." In *Proc., 32nd Int. Symp. on Automation and Robotics in Construction (ISARC)*, 1–8. Oulu, Finland: International Association for Automation and Robotics in Construction.

Preidel, C., and A. Borrmann. 2016. "Towards code compliance checking on the basis of a visual programming language." *J. Inf. Technol. Constr.* 21 (25): 402–421.

Preidel, C., and A. Borrmann. 2017. "Refinement of the visual code checking language for an automated checking of building information models regarding applicable regulations." In *Proc., ASCE Int. Workshop on Computing in Civil Engineering 2017*, 157–165. Reston, VA: ASCE.

Ramaji, I. J., and A. M. Memari. 2015. "Information exchange standardization for BIM application to multi-story modular residential buildings." In *Proc., AEI 2015*, 13–24. Reston, VA: ASCE.

Sadrinooshabadi, S., A. Taheri, I. Yitmen, and R. Jongeling. 2020. "Requirement management in a life cycle perspective based on ISO 19650-1 and CoClass as the new classification system in Sweden." *Eng. Constr. Archit. Manage.* 28 (9): 2736–2753. https://doi.org/10.1108/ECAM-03-2020-0203.

Salama Dareen, A., and M. El-Gohary Nora. 2013. "Automated compliance checking of construction operation plans using a deontology for the construction domain." *J. Comput. Civ. Eng.* 27 (6): 681–698. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000298.

Saldaña, J. 2021. *The coding manual for qualitative researchers*. Thousand Oaks, CA: SAGE.

Samarasinghe, T., P. Mendis, T. Ngo, and W. Fernando. 2015. "BIM software framework for prefabricated construction: Case study demonstrating BIM implementation on a modular house." In *Proc., 6th Int. Conf. on Structural Engineering and Construction Management*, 154–162. Moratuwa, Sri Lanka: Univ. of Moratuwa.

Shahtaheri, Y., C. Rausch, J. West, C. Haas, and M. Nahangi. 2017. "Managing risk in modular construction using dimensional and geometric tolerance strategies." *Autom. Constr.* 83 (Nov): 303–315. https://doi.org/10.1016/j.autcon.2017.03.011.

Shahzad, W., J. Mbachu, and N. Domingo. 2014. "Prefab content versus cost and time savings in construction projects: A regression analysis."

J. Constr. Eng. Manage., 2022, 148(12): 05022013

In *Proc., 4th New Zealand Built Environment Research Symp. (NZBERS)*, 1–17. Auckland, New Zealand: Massey Univ.

Sharma, S., A. Sawhney, and M. Arif. 2017. "Parametric modelling for designing offsite construction." *Procedia Eng.* 196 (Jan): 1114–1121. https://doi.org/10.1016/j.proeng.2017.08.069.

Singh, M. M., A. Sawhney, and A. Borrmann. 2015. "Modular coordination and BIM: Development of rule based smart building components." *Procedia Eng.* 123 (Jan): 519–527. https://doi.org/10.1016/j.proeng.2015.10.104.

Solibri. 2020. "Solibri model checker." Accessed May 31, 2021. https://www.solibri.com.

Solihin, W., and C. M. Eastman. 2016. "A knowledge representation approach in BIM rule requirement analysis using the conceptual graph." *J. Inf. Technol. Constr.* 21: 370–401.

Solnosky, R. L., A. M. Memari, and I. J. Ramaji. 2014. "Structural BIM processes for modular multi-story buildings in design and construction." In *Proc., 2nd Residential Building Design & Construction Conf.*, 201–215. State College, PA: Pennsylvania State Univ.

Sun, C., S. Jiang, M. J. Skibniewski, Q. Man, and L. Shen. 2017. "A literature review of the factors limiting the application of BIM in the construction industry." *Technol. Econ. Dev. Econ.* 23 (5): 764–779. https://doi.org/10.3846/20294913.2015.1087071.

Tam, V. W., C. M. Tam, S. Zeng, and W. C. Ng. 2007. "Towards adoption of prefabrication in construction." *Build. Environ.* 42 (10): 3642–3654. https://doi.org/10.1016/j.buildenv.2006.10.003.

Tan, X., A. Hammad, and P. Fazio. 2010. "Automated code compliance checking for building envelope design." *J. Comput. Civ. Eng.* 24 (2): 203–211. https://doi.org/10.1061/(ASCE)0887-3801(2010)24:2(203.

Teo, E. A. L., S. L. Chan, and P. H. Tan. 2007. "Empirical investigation into factors affecting exporting construction services in SMEs in Singapore." *J. Constr. Eng. Manage.* 133 (8): 582–591. https://doi.org/10.1061/(ASCE)0733-9364(2007)133:8(582.

Thompson, J. 2019. "Modular construction: A solution to affordable housing challenges." *Cornell Real Estate Rev.* 17 (1): 90–97.

Tornatzky, L. G., M. Fleischer, and A. K. Chakrabarti. 1990. *Processes of technological innovation*. Lexington, MA: Lexington Books.

Vanyi Technology Ltd. 2021. "An artificial intelligence-based ACC system for 2D drawings." Accessed March 3, 2022. https://www.vaiplus.com/.

Vass, S., and T. K. Gustavsson. 2017. "Challenges when implementing BIM for industry change." *Construct. Manage. Econ.* 35 (10): 597–610. https://doi.org/10.1080/01446193.2017.1314519.

Wang, S., Z. Liu, Q. Hao, Q. Zhao, and X. Wu. 2021. "A survey on the development of data-driven compliance checking and government's purchasing AI for compliance checking in China." [In Chinese.] *China Eng. Consulting* 2: 68–79.

Yin, R. K. 2011. *Applications of case study research*. Thousand Oaks, CA: SAGE.

Yurchyshyna, A., C. F. Zucker, N. Thanh, C. Lima, and A. Zarli. 2007. "Towards an ontology-based approach for conformance checking modeling in construction." In *Proc., 24th Int. Conf. of CIB W78*. Delft, Netherlands: International Council for Research and Innovation in Building and Construction.

Zhang, J., and N. El-Gohary. 2014. "Automated reasoning for regulatory compliance checking in the construction domain." In *Proc., Construction Research Congress 2014: Construction in a Global Network*, 907–916. Reston, VA: ASCE.

Zhang, J., and N. El-Gohary. 2017. "Integrating semantic NLP and logic reasoning into a unified system for fully-automated code checking." *Autom. Constr.* 73 (Jan): 45–57. https://doi.org/10.1016/j.autcon.2016.08.027.

Zhang, R., and N. El-Gohary. 2019. "A machine learning-based method for building code requirement hierarchy extraction." In *Proc., 2019 Canadian Society for Civil Engineering Annual Conf.*, 157930. Montreal: Canadian Society for Civil Engineering.

Zhang, S. J., J. Teizer, J. K. Lee, C. M. Eastman, and M. Venugopal. 2013. "Building information modeling (BIM) and safety: Automatic safety checking of construction models and schedules." *Autom. Constr.* 29 (Jan): 183–195. https://doi.org/10.1016/j.autcon.2012.05.006.

Zhao, Y., X. Deng, and H. Lai. 2021. "Reconstructing BIM from 2D structural drawings for existing buildings." *Autom. Constr.* 128 (Aug): 103750. https://doi.org/10.1016/j.autcon.2021.103750.

Zhong, B., L. Ding, H. Luo, Y. Zhou, Y. Hu, and H. Hu. 2012. "Ontology-based semantic modeling of regulation constraint for automated construction quality compliance checking." *Autom. Constr.* 28 (Dec): 58–70. https://doi.org/10.1016/j.autcon.2012.06.006.