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Lessons Learned on Adopting Automated Compliance Checking in AEC Industry: A Global Study

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Abstract

Over the last decades, numerous Automated Compliance Checking (ACC) systems have been developed. However, ACC is still not broadly used in the real world today; little is known as to how ACC can be better accepted by the end users. This paper reports on a multiple-case study to learn valuable lessons from recent attempts to adopt Automated Compliance Checking (ACC) systems world-wide. Firstly, eighteen semi-structured interviews were conducted with twenty experts from eight countries and supplementary data (e.g. documents, product information, and literature) related to each case were collected. Secondly, the interview and supplementary data were then coded to develop prominent themes. Thirdly, through a cross-case analysis, twelve most determining variables that could influence the ACC adoption were identified. Three path models that explain the interrelationships between these variables and ten propositions that can guide future ACC adoption were deduced. The results indicate that the government should play an important role to facilitate ACC adoption through funding, policies, and incentives. This study also provides valuable information to software vendors for delivering ACC systems that meet the needs of the industry, and for innovation managers in the industry to develop appropriate adoption plans for the ACC technology.

KEYWORDS: Automated Compliance Checking (ACC); Building Information Modelling (BIM); Technology Adoption; Construction; Case Study;

Introduction

Every phase of the Architecture, Engineering & Construction (AEC) project lifecycle is subject to compliance with a variety of requirements, including contractual, regulatory, and standards (Soliman-Junior et al. 2022). The process of checking the compliance of a building to these requirements is a highly complex task that relies on human recognition and experience (Beach et al. 2015). In recent years, there has been momentum in the development of Automated Compliance Checking (ACC), a process of using software to assess building designs against compliance requirements without modifying the designs (Eastman et al. 2009). First, new ACC approaches have been developed to digest legal requirements in natural language (Zhang and El-Gohary 2019) and make the technology more practical and easier to use by end-users (Dimyadi and Amor 2019). Furthermore, the advent and increased uptake of Building Information Modelling (BIM) provides the opportunity to describe the AEC projects through object-oriented data models (Eastman et al. 2011). Generally, rules representing compliance requirements are either hard-coded into checking software or represented for both human-readability and machine-processability (Amor and Dimyadi 2021).

With the advancement and maturity of ACC technology, there is a pressing need to understand how wide adoption of ACC can be facilitated. To meet this need, Zou et al. (2022) investigated New Zealand (NZ) off-Site manufacturing industry's readiness for ACC and developed a high-level ACC adoption roadmap with key actions for NZ. Another study by Beach et al. (2020) conducted a survey within United Kingdom (UK), which suggested a set of obstacles that prevented the adoption of ACC and proposed a vision for future ACC development and implementation. However, both efforts were regional studies and failed to explain the interrelationships among these obstacles (i.e., mechanisms of ACC adoption). These limitations prevent technology firms, policymakers and practitioners from understanding how and why ACC can be adopted in the AEC industry. To investigate what determining variables and mechanisms influence the ACC adoption in the AEC industry, this paper reports a multiple-case study that focuses on learning valuable lessons and experience in adopting ACC systems from the international efforts and interpret evidence from these global attempts into theoretical understanding.

Related work

ACC has been an active research topic for more than 50 years. A number of ACC implementations have appeared over the last two decades and have been extensively reviewed (Dimyadi and Amor 2013). Examples of these include CORENET's ePlanCheck in Singapore, Solibri Model Checker (SMC) in Europe, SMARTcodes, UpCodes, AutoCodes in the United States (US), DesignCheck in Australia, KBIM in Korea, and ACABIM in NZ. The ePlanCheck was considered the most successful recent implementation at the government level as it was commissioned by the Building Construction Authority of Singapore and involved many industry stakeholders (Goh 2007).

Prior to the turn of the millennium, researchers and software vendors dedicated years of effort to developing various digital representations of buildings, creating a challenge for downstream software applications, including traditional ACC systems to access the right data from proprietary digital models. The historical issue of lacking a platform-neutral open digital data exchange is being addressed by the emergence of the Industry Foundation Classes (IFC), standardised as an International Organisation for Standardisation (ISO) standard for open BIM (ISO 2018).

The immaturity of technology was considered as the main barrier leading to the lack of ACC adoption (Beach et al. 2015), which can be explained through two aspects (Eastman et al. 2009). First, the ACC systems are limited in capabilities in checking both regulatory and non-regulatory requirements. Secondly, the data generated from the design stage is insufficient to support the derivation properties and relations for ACC. To address these technical barriers, new ACC methods and systems were recently developed. These efforts include the ACABIM system developed in New Zealand (NZ) that employs a human-guided automation philosophy for compliance checking (Dimyadi and Amor 2019), artificial intelligence approaches to requirements interpretation for compliance checking (Zhang and El-Gohary 2019). A number of studies (Dimyadi and Amor 2013; Eastman et al. 2009; Hjelseth 2015; Krijnen and Van Berlo 2016) have extensively reviewed the technological development of ACC. Evidently, ACC technology is becoming mature and will likely be used in the day-to-day working environment in the industry in the coming years.

According to the literature (Lee et al. 2003; Tornatzky et al. 1990), success factors towards the adoption of new technologies include not only technological development but also human perception and policies. Most of the existing ACC literature focused on technology but failed to consider the current ACC adoption challenges. To better understand these adoption challenges from an end-user perspective, Beach et al. (2020) recently conducted a survey study within the UK. This study ascertained a set of obstacles that prevented the wide adoption of ACC in the AEC lifecycle and proposed a vision for future ACC development and implementation. However, this research has three major limitations. First, it only surveyed industry professionals who might not be familiar with ACC. Secondly, the study failed to explain the interrelationships between these obstacles. Thirdly, it only focused on UK context and ignored important ACC adoption attempts in other countries, e.g. Australia, US, NZ, South Korea.

To summarise, there has been no existing study that has analysed the global efforts of ACC adoption and can explain what determining variables and mechanisms influence the ACC adoption in the AEC industry.

Research methodology

A multiple-case study (Yin 2011), which involves eight different cases, was conducted to explore the key variables and mechanisms that influence the adoption of ACC technology in the AEC industry. This method was selected because (1) it enables the exploration of a contemporary phenomenon in depth and within its real-life context, (2) compared with the single case study, the multiple-case study is recognised as being more robust and its results are more compelling (Yin 2011). In addition, the eight cases described ACC adoption in eight different countries. As a result, the method employed in this research could also be seen as a multi-country analysis. The multi-country analysis involves the collection, analysis and comparison of data from multiple countries, and enables researchers to uncover patterns, attitudes, similarities, differences and new opportunities (Sunström 1999).

Case selection

A case study is defined as an in-depth, detailed examination of a particular case (or cases) within a real-world context (Yin 2013). It has been widely used for research in both natural and social sciences. Gerring (2017) pointed out that the units in case studies can vary according to different research nature and subject areas, ranging from social groups (for sociologists), the individual (for psychologists), the firm (for economists) to nations or organisations (for political scientists). For ACC adoption, each country has its unique contextual characteristics in terms of policy, building code, regulatory environment, building typology, building consent processes, stakeholder requirements, etc. All these embedded factors influence and shape the development of ACC technologies, leading to the emergence of various ACC systems that can fit into the existing compliance workflows for each country (e.g., KBIM ACC system in South Korea (Kim et al. 2020), ACABIM system in NZ (Zou et al. 2022)). Based on this observation, this study treats the experience and lessons of ACC adoption in each country or region as an individual case. Purposeful sampling (Palinkas et al. 2015) was used to identify and select information-rich cases related to ACC adoption. To ensure the cases can be situated within the context of this research, three main sampling criteria were developed to govern the selection of case studies, as below.

(1) The ACC technology reported in the case study should be at least a functional prototype system that can fully or partly automate the compliance checking processes in the building lifecycle.

(2) The ACC system(s) should have been used in a real working environment or been tested in at least one pilot project. This will ensure the selected case study contains some lessons and experience on the adoption of ACC systems.

(3) The case study must have multiple key stakeholders involved. This will help unveil not only technology-related experience but non-technology adoption lessons in the organisational, multi-disciplinary, collaborative, environmental, and other contexts.

Data Collection

Table 1 provides an overview of the sources that were used to collect data for the case studies. The profile of interviewees and key interview questions can be found in Appendix I and Table 2. In total, eighteen interviews with twenty experts involved were conducted with key stakeholders. Sixteen interviews (with eighteen participants) lasted varying from 45 to 90 minutes (average of 60 minutes) and two interviews (with interviewees P and Q) were conducted via emails due to language and availability issues. The stakeholders who were invited to attend the interviews were involved in ACC

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adoption in their countries, held important positions in their organisations (e.g. Chief Technology Officer leading the development of ACC systems, building consent officer conducting the pilot testing of ACC systems), and had in-depth knowledge of ACC adoption experience. A semi-structured method was adopted to allow adaptation of questions and accommodate the interviewee through follow-up questions and further explanations relevant to the adoption experience (Rowley 2012). All the interviews were recorded and transcribed.

Along with this interview data, documents, ACC product information and other textual data were provided by the interviewees or collected through the Internet, to validate the emerging findings, enrich the interview data to describe the big picture, narratives and characteristics of each case (Creswell 1999).

Table 1 Overview of data sources per case

Cases	Sources of Evidence	Details
1: Australia	Documents	• Product information (CRC Australia 2005), • literature (Ding et al. 2006)
	Interview	Two interviews with ACC expert (who was leading the development of DesignCheck) and another ACC expert (who was involved in the development of DesignCheck).
2: China	Documents	• Product information (Nanjing Government 2021; Nanjing Government 2022), • literature (Wang et al. 2021)
	Interviews	Four interviews with the ACC researcher (who had >3 years ACC research experience), BCA officer (who was involved in a major ACC pilot project), design engineer (who was involved in a major ACC pilot project in China), ACC expert (who was involved in the development of one ACC software)
3: Estonia	Documents	Project report (FIG 2019)
	Interview	One interview with two ACC experts (who were involved in the development of ACC software in Netherlands/Estonia)
4: NZ	Documents	Case study report (NSC-BBHTC 2019), literature (Amor and Dimyadi 2021; Dimyadi and Amor 2017; Dimyadi et al. 2020)
	Interviews	Four interviews with a BCA officer (who tested ACC systems and conducted a research project on ACC at the master level), an ACC expert (who had >30 years BIM/ACC research experience and was involved in the development of ACABIM), two standardisation experts (who worked in the national standards body for NZ).
5: Singapore	Documents	Literature (Amor and Dimyadi 2021; Goh 2007; Khemlani 2005)
	Interviews	Two interviews with one ACC expert (who was recently involved in a major ACC development project in Singapore) and another ACC expert (who had >20 years ACC research and development experience)
6: South Korea	Documents	Literature (Amor and Dimyadi 2021; Kim et al. 2019; Kim et al. 2020)
	Interview	Three interviews with an ACC researcher (who has >14 years ACC research and development experience and has been involved in the KBIM ACC system), a researcher (who has >20 years research experience in BIM and ACC, and was leading the development of ABIMO Checker), and one ACC expert (who has been developing the KBIM ACC system)
7: UK	Documents	Project report (CDBB 2019)

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	Interviews	Two interviews with the ACC expert (who had >10 years ACC research and development experience), and the construction expert (who had much experience in preparing building permit applications)
8: US	Documents	Literature (Kim and Clayton 2010; O'Brien 2021)
	Interviews	Two interviews with ACC researcher (who has been an active ACC researcher >10 years, collaborated with ACC technology firms, and had commercialisation experience on ACC research), and ACC expert (who has been an active research in ACC and computing in engineering for >30 years, and is one of the founders of SmartReview)

Table 2. Key interview questions

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

Data analysis

A within-case analysis was firstly conducted. In qualitative research, data analysis refers to the process of systematically searching and arranging the interview transcripts, observation notes, or other non-textual materials to draw an in-depth understanding of the phenomenon (Sari and Bogdan 1992). In this study, the content analysis included an iterative process of coding the interview data using Nvivo 12 (Edhlund and McDougall 2019) qualitatively in two cycles, as recommended by Saldaña (2015). To reduce the individual subjectivity and ensure the reliability of the coded data, using multiple coders is recommended (Berends and Johnston 2005; Evans 1996). In this project, the coding process involved two independent coders and another supervisor. Both coders were key researchers of this project and had good knowledge in the subject area of BIM and ACC. The first cycle of coding was structural coding which applied a content-based or conceptual phrase representing a topic of inquiry to a segment of data that relates to a specific research question used to frame the interview. It resulted in defined codes from the data matrix being associated with multiple subcodes. For example, "the accuracy of the results from existing ACC technology is questionable" was coded as "Inefficiency of technical capabilities". The latter cycle of coding was focused coding which categorised coded data based on thematic or conceptual similarity. For example, the codes of "Inefficiency of technical capabilities" and "manual practice of building code compliance" were grouped into the theme of "technological barriers of ACC". In addition, the possible contextual relationships in the interview quotes were highlighted to support further analysis. For instance, "The industry does not have money and time to train professionals to use BIM; (Government) funding is needed to facilitate ACC adoption" revealed a possible relationship between the industry, policymakers and ACC adoption. Through this step, the most outstanding codes were identified, themes were developed, and possible contextual relationships were highlighted.

The agreement between the two coders on allocating text segments into categories was measured by Cohen's *kappa* (Cohen 1960)

$$k = \frac{p_o - p_e}{1 - p_e}$$

where p_o is the relative observed agreement between the coders, and p_e is the hypothetical probability of chance agreement. According to Landis and Koch (1977), in most cases the values of k range between 0 and 1, and agreement is considered as sufficient based on strengthen when $k \geq 0.8$.

The k values for the eight cases analysed were: 0.90 (Australia), 0.89 (China), 0.98 (Estonia), 0.95 (NZ), 0.94 (Singpore), 0.86 (South Korea), 0.85 (UK), 1.00 (US) respectively, with an average of 0.92. Then the two coders discussed all inconsistencies and discrepancies to improve mutual understanding. During this process, most inconsistencies and discrepancies were easily resolved when one coder pointed out the other coder lacked sufficient understanding of the context, had overlooked or had interpreted the language differently. For the remaining inconsistencies and discrepancies that the two coders were unable to reach an agreement after joint discussion, the supervisor was involved, all three participants reviewed and discussed these inconsistencies and discrepancies, and finally a resolution was reached.

Once the data for each case has been analysed and refined, a cross-case analysis took place following the recommendations of Miles et al. (2018). The case-specific determinants were extracted, and compared with each other to reach generic conclusions regarding the adoption variables. Twelve adoption variables were obtained after iteratively analysing the case data and repeating the cross-case analysis. In the meanwhile, a further analysis on possible interrelationships between adoption variables was conducted. Based on this analysis, three path models that can determine the adoption of ACC systems were deduced and ten propositions that can guide future adoption of ACC systems were developed from the eight cases.

Data validation

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 to make. To validate the results of this study, the adoption variables, path models and propositions were summarised and sent back to the interviewees for verification and feedback. Their feedback was used to further improve the research results until a consensus was reached.

Findings

Case description

In this multiple-case study, eight countries were selected for comparative analysis: Australia, China, Estonia, NZ, Singapore, South Korea, UK, US. Table 3 summarises the approaches of digital technology adoption in AEC industries of the selected countries. It can be found that Australia, Estonia, NZ and US implement a bottom-up approach; while the rest countries (China, Singapore, Korea and UK) adopt an top-down approach. According to Jiang et al. (2022), *bottom-up (i.e., industry-driven) approach requires a lower level of government intervention while the industry takes an active part; in contrast, top-down (i.e., government-driven) approach means that the government takes the lead and launches a series of policies (e.g. BIM mandates) to get the industry stakeholders involved*. Although these two digital technology adoption approaches exist, we have also observed a similar pattern across the selected countries, which is to build alliance of government, industry stakeholders, industry associations and academics to promote the research and development (R&D) and adoption of digital technologies. Each country is discussed separately as below.

Table 3. Approaches of adopting digital technologies in AEC industry

Country	Approach of digital	References

	technology adoption	(Jiang et al. 2022)	(Papadonikolaki 2018)	(Kim et al. 2019)	(Hosseini et al. 2016)	(Liu et al. 2017; Ma et al. 2022)
Australia	Bottom-up				✓	
China	Top-down					✓
Estonia	Bottom-up		✓			
NZ	Bottom-up					✓
Singapore	Top-down	✓				
Korea	Top-down			✓		
UK	Top-down	✓				
US	Bottom-up	✓				

In Australia, Australasian BIM Advisory Board (ABAB) was established around 2017 to build an alliance of key industry stakeholders, government, industry associations to coordinate and provide advice on harmonisation of BIM development across Australia and New Zealand (Built Offsite 2017). ABAB has no powers but focuses on integrating a whole of built environment approach to support best BIM practices, developing strategy, roadmap and standards, providing advice to both governments and industry. Around 2019, the Australian BIM Strategic Framework was published as the first key step to establishing a basis for governments to adopt a consistent national approach to BIM in major building and infrastructure construction projects (ABAB 2019).

Liu et al. (2017) reviewed the BIM adoption in China. Firstly, the central government has provided strong policy signal to encourage more use of BIM. For example, in 2011 the Ministry of Housing and Urban-Rural Development (MOHURD) issued outline of Development of Construction Industry Informatisation (2011-2015) and highlighted the nation will take BIM as core enabling technology to support digital transformation in Chinese AEC industry. Almost at the same time, the Ministry of Science and Technology (MOST) announced that BIM as a national theme in its 12th Five-Year Plan on Science and Technology Development. Various BIM national conferences, BIM seminars, BIM design competition, and BIM training have been organised raise the AEC industries' awareness on BIM. In addition, local governments and companies provided incentives (e.g., reward of extra points for BIM applications in design competitions) to encourage them to adapt to the digital age.

The Estonian Digital Construction Cluster (EDCC) was launched in 2019 to improve the digitalisation of the AEC industries in Estonia (ECSO 2020). EDCC was in partnership with four government departments (Ministry of Economic Affairs and Communications, Estonian Road Administration, Tallinn City Council and Enterprise Estonia (national investment agency), and the Estonian Association of Information Technology and Telecommunications (ITL)) and brings together a broad range of key stakeholders in the construction lifecycle value chain. The main objectives of EDCC include: helping AEC industries better understanding and use digital technologies; improving collaboration between different stakeholders; enhancing digital skills across the whole AEC sector.

In New Zealand, a nationwide alliance between the construction industry and government, known as BIM Acceleration Committee (BAC), has been established in 2014 to promote the update of BIM in New Zealand (BAC 2017). BAC has five main roles: developing and maintaining the NZ BIM Handbook (which is a non-mandatory document to guide practitioners to use BIM); conducting annual BIM update survey; providing case studies to demonstrate the capability and successful experience of BIM use; providing training; organising conferences and events.

In Singapore, policies of the central government are easy to implement; as a result, Singapore has taken a government-driven approach to increase the BIM use in the industry (Jiang et al. 2022). Since 2015, the Building and Construction Authority has mandated all new building projects with gross floor areas of 5,000 m^2 and above to submit their architectural, structural, and mechanical, electrical, and plumbing (MEP) plans in the format of BIM (Liao et al. 2020). The Building and Construction Authority of

Singapore also developed the second Singapore BIM roadmap to encourage the local construction value chain to adopt BIM in a more collaborative way (Shen et al. 2016).

South Korea is among the most proactive countries of developing and using BIM and digital technologies (Lee et al. 2015). In 2017, the Ministry of Land, Infrastructure and Transport of Korea provided around US$25 million funding to support the Korean BIM Standards (KBIM) project (buildingSMART Korea 2022), which was the largest ever BIM R&D project in the history of Korea. KBIM was led by buildingSMART Korea, with participation of more than 100 companies, universities, government agencies and research institutes. It includes three phases: OpenBIM standard platform and application technology development; Development of openBIM-based Automatic Rule-Checking (ARC) Technology; OpenBIM-based integrated facilities management technology.

The UK government announced its Construction 2025 strategy (HM Government 2013) in 2013, aimed to meet objectives of reduction of initial and whole life costs of built assets, improvement in project delivery and service export, and reduction of carbon emissions. This document clearly defines a national strategy to invest in digital technologies to transform the whole sector as efficient and technologically advanced. To support this vision, UK BIM Task Group (2011) has further developed a report which outlines milestones, strategies for academic support, training, industry involvement and legal issues resolution. UK government policy is in place to mandate level 2 BIM from 2016 (Georgiadou 2019). Construction Innovation Hub, a new partnership among industry bodies, policymakers, practitioners and academics, has been recently established to drive innovation and address key challenges in the construction industry (Construction Innovation Hub 2022).

US has selected a bottom-up approach in promoting BIM due to its unique BIM adoption culture: various local state governments and different organisations are developing separate approaches. Even so, some joint efforts across the whole country have been also observed. According to Jiang et al. (2022), the US General Services Administration (GSA) established the first National 3D-4D-BIM Program in 2003, which require that all GSA-funded projects that used BIM should be submitted to the office for final approval in fiscal year 2007 and beyond. Between 2006 and 2017, GSA published eight series of BIM guidelines to cover the whole lifecycle of construction projects. The National Institute of Building Sciences (NIBS) has collaborated closely with governments, industry, researchers and practitioners, to develop and maintain its BIM guideline, build alliance, and provide BIM training and forums.

Table 4 presents the characteristics of ACC systems, and the context of the adoption in each country. For all selected countries, adopting ACC to help the Building Consent Authority (BCA) conduct building consent/permit assessment faster, easier, and more reliable was the primary business interest. BCAider and DesignCheck of Australia were among the earliest ACC systems in the world; however, they have not stood in the test of time and have no further development plans in place. Although ACC has not been fully adopted in practice in all cases, these countries have transitioned or are in the process of transitioning from paper-based workflows to e-submission systems (i.e. submission, assessment and approval using digital data). In addition, they have plans to develop new ACC systems or improve existing e-submission systems, translate their building codes into machine-readable rules, and build a partnership with relevant stakeholders to demonstrate the benefits of ACC systems.

Table 4. Brief description of ACC adoption in the eight selected countries

Cases	ACC system	ACC adoption	Multiple stakeholder involvement	References
Australia	In 1991, an expert system, BCAider, that can help designers, building surveyors and educational trainers to apply the Australian building	BCAider was licensed for distribution by Butterworths from 1991 for about 6	Yes	(Dimyadi and Amor 2013; Ding et al. 2006; Ward 2014)

	code to buildings, was released by the Commonwealth Scientific and Industrial Research Organisation (CSIRO). In 2006, CSIRO announced DesignCheck, a new system based on IFC for compliance assessment against building codes. DesignCheck used Express Data Manager (EDM) as the software integration platform for encoding design requirements from building codes.	years and then by CBH, who stopped distribution around 2005. DesignCheck was not commercially used and there has been no plan for further development.		
China	Since around 2015, the local governments (e.g. Shanghai, Nanjing) started the transformation from paper-based documents to e-submissions (i.e. submission, assessment and approval using digital data). The government of Nanjing led the development of a BIM-based e-submission system in collaboration with software firms, consultants and construction companies. ACC has been integrated into the system to check those rules that can be easily quantified. There has been a plan for further development of the system.	The BIM-based e-submission system of Nanjing has been commercially used. The first building consent approval using the system was granted in 2021.	Yes	(Nanjing Government 2021; Nanjing Government 2022; Wang et al. 2021)
Estonia	In 2019, A Netherlands-based software company, Future Insight Group, cooperated with European Commission's Structural Reform Support Service and demonstrated a BIM-based process for building permits in Estonia. The building permit assessment system is a web platform based on open BIM components (e.g. (BIM Server, BIM Surfer, Voxel Server). It has embedded with smart algorithms to automate some labour-intensive manual checks.	An Estonian proof of concept was conducted using the system developed by Future Insight Group.	Yes	(FIG 2019)

New Zealand	In 2019, Compliance Audit Systems Limited (CAS) introduced ACABIM, a cloud-based automated compliance audit system. ACABIM is built upon the philosophy of human-guided automation, taking IFC model, Business Process Model and Notation (BPMN)-compliant workflow model, and Legal Knowledge Model (LKM) as input to assist human against the information in the BIM model is audited. Most recently, a project to translate a number of priority consenting documents from the NZ Building Code (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)	Since 2019, CAS has conducted a couple of pilot projects, in collaboration with building consent authorities and construction firms, to test the feasibility and prove the benefits of ACABIM system in New Zealand.	Yes	(Compliance Audit Systems Limited (CAS) 2019; Dimyadi et al. 2020)
Singapore	In 1995, the Building Construction Authority introduced the CORENET (Construction and Real Estate Network) system to check 2D plans for compliance. It upgraded the system in 2002 as CORENET ePlanCheck to enable the processing of 3D IFC models. The system implements ACC against two major domains: architectural and building services. Recently, the Singapore government has been collaborating with local vendors to develop the next generation of ACC system, called CORENET-X.	The CORENET ePlanCheck was commissioned by the BCA and has been commercially used.	Yes	(Amor and Dimyadi 2021; Goh 2007; Khemlani 2005)
South Korea	The South Korean government started accepting non-visit	The KBIM building e-Submission system	Yes	(Amor and Dimyadi

	digital submissions for building permit assessment in 2008. A system called SEUMTER was developed and expanded for nationwide use in 2012. Recently the government is in collaboration with buildingSMART Korea and a number of institutions to improve SEUMTER to be a new ACC system, called KBIM. KBIM employs KbimCode, computer-processable rules translated from building codes.	has been tested through several real projects.		2021; Kim et al. 2019; Kim et al. 2020)
UK	The Digitization of Requirements, Regulations, and Compliance Checking Processes in the Built Environment (D-COM) network was established around 2018 to create a new digital ecosystem to support automated and easier regulatory compliance in the UK.	In 2014, the National Building Specification (NBS) completed a pilot project, in collaboration with Butler & Young, to demonstrate the systems to perform ACC using BIM models.	Yes	(CDBB 2019; National Building Specification (NBS) 2014)
US	SMARTreview was introduced around 2013 and has been used by architects to check compliance with portions of the International Building Code. In 2016, UpCodes AI was founded to employ natural language processing to read from building code database and check BIMs against those code requirements. Both software tools work as plug-ins of Autodesk Revit.	Both SMARTreview and UpCodes AI have been commercially used. In addition, a close collaboration between academia and ACC technology firms has been observed to explore artificial intelligence ACC solutions.	Yes	(Amor and Dimyadi 2021; Clayton et al. 2013; Kim and Clayton 2010; O'Brien 2021)

Contributing variables and path models

During the process of coding interview data and comparing cross-case results, a total of twelve key variables that affect the adoption of ACC systems were identified. The variables and their quotes in each case study are presented in Table 5. In the meantime, interrelationships between some of these variables were found in the context of these quotes. Through evaluating these variables and their possible interrelationships in each of these eight case studies, three path models that can explain the mechanisms of ACC adoption in the AEC industry were deduced (Figures. 1-3). The rest of this section describes the three paths and formulates associated propositions. See Appendix II for details about the path development with supporting interview quotes and literature.

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Table 5. The identified variables affecting the adoption of ACC systems

Variables	Australia	UK	Singapore	New Zealand	Estonia	Korea	China	US
V1: Government Support	The industry can be influenced by the governing parties' focuses. One major impediment is the upfront investment to support ACC development in the long term. The funding should cover not only the technology development but its implementation in industry. Unless the government puts ACC in a requirement in the end, the industry is not sufficiently coherent to make the change itself.	The government can provide a driving force by insisting on the digital audit trail. Business incentives are needed to encourage ACC adoption, such as reduction of costs or change in business models.	To push ACC implementation, the government starts accepting BIM e-submission and provides financial support for industry adjust from 2D to BIM environment.	Most local councils are not providing a driving force for ACC development and adoption. Councils should publish a roadmap to lead the direction for ACC uptake. Funding is needed for ACC development, but cost is a big concern for the industry.	The government needs to take the lead, e.g. to set up fast tracks for contractors using ACC systems. In 2019, the government provided most funding for us to build the first ACC demo with the aim of gaining experience and showing people the possibility to get support.	The government has power to change the building codes, so should lead the development of ACC products and their update. Slow adoption is because learning BIM and ACC applications is extra job for end users. The industry does not have money and time to train professionals to use BIM. Funding is needed to facilitate ACC adoption.	To push ACC, the government should provide guidance and support in terms of policies. The central and local governments have been exploring BIM-based audit in many cities and have invested in developing BIM-based audit systems and City Information Modelling (CIM) platforms.	Government is also considered as one of the main potential client of ACC technology who needs to improve efficiency of design checking. The driving force of ACC technology is different state to state due to the different jurisdictions across the nation.
V2: Human resistance	People are reluctant to try new approaches as they are not certain about the risks involved.	In order to overcome scepticism and resistance to change guidance will be produced, targeted to specific audiences, to convey the aims/objectives/ benefits of digitisation of regulations/requirements. Additionally, will support more complete and consistent BIM usage. This will also grow wider awareness.	The main barrier is the human factor. The industry has a lot of reluctance to change. There is always a pushback, where a major concern is the additional effort in BIM modelling.	One of the natural barriers to ACC uptake is human resistance. People understand it is good but hesitate to take action. The overhead of learning and using ACC is high. Their attitudes are not changed by what other countries have done.	The inputs into the ACC systems is a barrier for the contractors to adopt the technology.	The problem is people. The ACC project has been going on since 2012, but industry acceptance is very difficult. People don't want to change to 100% BIM based e-submission.	Human factors, organisational factors and management factors need to be considered, i.e. whether the technology enables better work practice. It's only meaningful to perform BIM-based ACC if the project is designed in BIM. However, designers are more reluctant in adopting BIM compared with contractors, because there is an imbalance in the benefits/profits they get.	The transition into digital modelling and BIM based practice requests the a planned process and understanding of current practice in the industry. The ACC technology adoption may take the hold generation. That could be 30 years or more. The collaboration of the government and the industry are the key to push the adoption. With the BIM application ready in the

									industry, the technology development can mainly focus on the IFC model processing for the government.
V3: Industry readiness and innovativeness	The industry is reluctant to change as there lacks real incentives to change in the culture. The industry needs to learn how to how it will get benefited from the technology.	Build a product or process to meet majority of needs, trial and test in representative environment and capture key metrics, refine and ready for scaling.	21 years ago, an ACC solution was developed in Singapore, but the industry wasn't ready. Success factors for ACC adoption include a good coverage of standards, skills, critical mass (enough proportion of industry adopted), obvious benefit for industry.	Incremental steps are needed to change the NZ industry culture for accepting and adopting ACC solutions. There has to be a few visionary people or a triggering event to lead the change of the industry.	Estonia is one of the most digital society. 80% of the designers and contractors are using BIM. Government people can work with IFC files .	Industry acceptance is a challenge, especially for field workers and architects. Korea has relatively low adoption of BIM by small and medium-sized architectural firms.	In current practices, BIM models are made by "BIM centre" in the design firms based on 2D drawings. 3D design using BIM platforms should be adopted.	The ACC needs from the industry are coming from the workforce shortage and the productivity challenges due to increasing number of project. ACC relies on BIM; however, the reality is industry people do not use BIM well. The US ACC technology is being pushed into a higher level of automation. There are several commercial ACC systems available on the US market, such as SMART CODES. There are academic groups researching into cutting edge technology to further support the ACC, such as deep learning and natural language processing.

V4: Education and training	Education is a major impediment to BIM and ACC uptake.	Develop audience specific training and guidance, establish methods for user feedback and continually refine alongside pathways for enhancement.	There is also need to retrain government officers to work with 3D.	It is key to train building consent compliance officers on how BIM and ACC works.	-	Education has been provided for future generation of the industry, but current industry people are reluctant to change.	Education needs to be provided in universities on 3D design tools and BIM, so students will have the intention to learn BIM when they start their career, which is beneficial for BIM uptake. Senior designers need to be trained to use BIM and to know the values of BIM so they can proactively learn about it. To better promote ACC, design companies need to know more about the ACC system and improve their design quality.	The industry needs to firstly recognise the value (of BIM and ACC).
V5: Stakeholder engagement	ACC should go through incremental development to involve the users from early stage and ensure their needs are addressed.	Consult with stakeholders (to include academia, industry and policymakers) to identify prospective use cases and gather requirements.	Top driver is government. Second driver is consultation with industry. The motivation for industry to use ACC is the evidence of efficiency improvement.	The ACC system needs to be audited or certified, i.e. pass a robust quality assurance procedure to ensure the accreditation of its results. ACC tool was developed replicating the councils' checking procedures to gain trust. The accreditation needs to be acknowledged by councils and should be reviewed at regular intervals.	Third success factor is to involve all stakeholders to improve the legislation. The real challenge is the different stakeholders and their demands, so need to involve the stakeholders.	KBIM Collaboration was developed based on openBIM as the platform for information storage and exchange among stakeholders.	To improve the user experience, there is a need to optimise, improve and upgrade the existing building permit assessment system using ACC technology.	User friendliness is the top factor of technology adoption. The users do not care about the technology behind the scenes but how the technology to be tailored to fit the needs and workflows of the themselves. The key of successful technology development and implementation is to understanding the expectations and needs of the potential clients at the early stage. The developers also need to understand

								the factors relevant to technology adoption . Learning the options of user friendliness from the stakeholders to determine the technology developing direction. The user friendliness includes different aspects such as how to fit into the current practice and the user expectations.
V6: Pilot projects and case studies	DesignCheck was tested by private and public design organisations for validation and feedback. A market leader and building consent authority in the construction industry should take it up. Then they can demonstrate the benefits of ACC inside and outside the company.	A good case study or pilot project would be a strong push for the government to accept digitalisation.	Stakeholders have been involved in the creation of modelling guidelines (in ACC pilot projects).	Successful cases from other countries can provide driving force for public policy; then successful local cases in NZ are needed to convince the industry. Having a national checking process agreed by councils could encourage development of related tools.	-	-	Two cities were selected for piloting BIM based compliance checking, where the government is pushing BIM through mandatory means, e.g. mandating 3D audit for public projects.	Currently, there are only a handful of experts that are well-versed in drafting sophisticated Form-based Codes (FBCs); therefore, additional trial and error are expected.

V7: Tangible benefits	It is important to show the stakeholders how they will be benefited using ACC.	Benefits of ACC in terms of efficiency and cost reduction can be a big driver. Trust needs to be developed for ACC tools and the results they produce.	The driving force for the government to use ACC is building quality, productivity improvement, higher efficiency and being less reliant on human. Automation can help reduce the workload so officers can focus on more complicated cases.	The benefits of ACC needs to outweigh the value of current practice. The industry needs to know how the council charges for ACC service, and whether it is fast enough to be worthwhile. Currently it is difficult to test how much time BIM or ACC saves for the consenting process, so there lacks evidence to convince people its efficiency gain or provide assurance on its benefits.	The issue is that we fail to build what the users want. The intention for developing our ACC solution was to gain experience and build a demonstration for the industry's internal communication to convince the government its usefulness and get the support they need.	The government wishes to enhance building quality and have less code violations through ACC.	The most important factor is its cost. Profit (or reduction in cost) is the driver for design companies to adopt ACC.	-
V8: Appropriate marketing	-	-	-	There are mistrust on the benefits of ACC technology. A big problem is that the marketing for the technology tend to oversell and promise for functions that are not yet fully developed.	-	-	The adoption is fundamentally related to the actual benefits but not the marketing strategies. Exaggerating or overpromising the benefits of technologies would result periods of inflated expectations and disillusionment.	The industry buy-in is critical for technology adoption. The commitment of the clients including industry and government required to deal with different associated factors such as legal, financial and risk.

V9: Technology integration	The problem with the DesignCheck was how to interpret drawings. BIM should be the base of ACC, which require international agreement on APIs. The existing ACC tool (e.g., SOLIBRI model checker) was found having limitations due to its black-box nature. To help industry accept ACC technology, you need to have really good interfaces, all aspects of interfacing.	Currently the big limitation is lack of integration of technologies and tools.	The ACC software (we developed) had a wide definition for checking that allowed 2D drawings to be checked. The ACC system should be open to allow anyone to change rules and regulations instead of hard-coding in the rules. It's better to be an open system to avoid copyright issues.	The improvement of BIM technology, smart standard and IFC standard provide strong representation for the ACC technology. However, the technology is far from implementation stage. The future progress and the problem are uncertain in this stage. The optimised outcomes need to integrate industry knowledge, computer expertise, user community, legislative bodies.	The ACC system (we developed) is web-based and linked with the national digital twin, where IFC files can be viewed in the digital twin.	ACC related BIM applications require e-submission systems, changes from traditional building code to KBIM code system, and the development of mobile, web, and cloud-based viewers. Efforts are being made to improve usability (of KBIM) through consultation with field designers. If the regulatory compliance review is made through the use of ACC in the regulatory process, it will be a great opportunity for the diffusion of related technologies and technology development.	ACC currently has two directions, 2D drawing checking and 3D BIM checking. BIM-based ACC has just started to develop, test runs were performed at a few pilot cities. From the industry's perspective, the cost of using BIM in many projects is still too high. There is still a huge demand in CAD audit, so the industry would like to have both pathways. The government is pushing the digitalisation of building information (at urban scale), where building a CIM platform is the key, involving BIM, internet and GIS. The government is leading BIM uptake because BIM data will help building up the CIM platform.	The implementation of IFC model is critical. That directly impacts the value of technology building on top of the IFC model. In the US, federal agency has adopted the IFC standard for infrastructure type of projects. That encouraged the development of the technology.

V10: Modelling standards	Libraries of building objects and systems should be incorporated in BIM software, as consistency in naming between different software is necessary for rule checking to work. Modelling standard and information standard are critical. ACC will benefit if the model is good and consistent. Minimising modelling effort can make it easier for industry to adopt meanwhile balance the requirement of the model.	-	There needs to be a standard for BIM modelling to make all data meaningful.	The industry needs to provide required information in BIM in a specific format, such as correct naming of IFC objects. Human factor is the main barrier as ownership of responsibility is not clear for model quality.	Standardisation of BIM modelling is key. For instance, the contractors may standardise models in their own company, but the standard is different across the industry.	The model is always a problem. There are often inconsistencies and errors in BIM models. Architects need to provide BIM models suitable for code checking. It's better to have intelligent translators or modellers that allows ACC, without regulating people how to create their models. For ACC, it is necessary to follow appropriate guidelines in the modelling process, but it is difficult to consider this in the field. There are guidelines that must be followed when creating a BIM model in order to review various requirements.	Setting up standards for models in early stage and perform ACC will help the model standardisation problem between designers and contractors. The lack of model standardisation causes inconsistency between model and the actual building, so the value of BIM in operation phase hasn't been recognised. The adoption of ACC system will put restrictions on designers to make the models in a standard way. The standards for model deliverables set by government are not strictly followed because they are not mandatory. The bad quality of data and BIM models may cause problems (to further ACC applications).	The beta testers really liked our ACC system, but found it really difficult to use. We analysed what made it difficult to use. We realised that it wasn't our software. It was the quality of BIM that they produced and fed to the software.

V11: Information standard and requirements	Modelling standard and information standard are critical. An enabler for code checking is good quality BIM models, but some companies cannot provide good BIM models, which makes code checking hard to implement。	-	The ACC solution to make people accept 3D is to help them understand how the model works and trust the tool. So an information standard for them is critical. To unify all BIM standards, an information standard and cloud service are being developed. Standardised data would bring new possibilities and benefits in the future.	Accuracy and quality of BIM information is fundamental for the outputs from ACC tools.	Algorithm-based checking is preferred compared with rule-based checking. Top success factor is the use of open standards like IFC and BCF.	Building code related regulations can set submission requirements for models, so that architects create models suitable for code checking. For ACC, objects must have appropriate information. There is a need for an information framework that can clearly define in what form the client will use the BIM model. Clear requirements should be defined prior to design and construction and reflected in the model. We are conducting research on technology that can automatically supplement the model with insufficient information in the BIM model that does not comply with the modelling guide.	BIM still has limitations but the government believes it's the future trend so they are promoting its uptake. The government wants to push the standardisation of BIM through building up the 3D audit platform. Clients may have requirements for designers in terms of data standards. The templates set by design companies have variations and are difficult to control. Creating models based on 2D drawings can be very inconsistent and cause many problems.	For ACC, the BIM model has to be complete and makes sense, about not only the 3D model, but also the non-graphic, non-geometric aspects. Until the industry gets more standardized in representation (of information in BIM). I don't think there's much potential for ACC with those parts of the building code. We identified the parts of the building code that we believe that architects put in the model in every project intensely a standardized way, and so therefore they can be checked.
V12: Standard of interpreting building code	-	The building code in UK is frequently updated. There needs to be a standard way for regulations to be represented in machine readable form. The government is working on digitising the documents, and should be responsible for ensuring regulations are compatible with new technologies.	It is a problem that people from agencies interpret rule regulations differently. The current solution is to quantify the code as much as possible to avoid disagreement.	The NZ building code is improving in terms of accessibility and computer readable. A small body of standards has been converted to XML and can be used for ACC, but majority of codes are still in PDF. Translating	Existing regulations are not precise enough for developing the automated system, the regulations need to be changed to a more sensitive way to achieve 100% code translation.	The building codes need to be upgraded to make ACC mandatorily applied for some projects. There can be intelligent translators or modellers to allow ACC to recognise the model instances etc. The	The scope of ACC is mainly quantifiable regulations. Adding regulations that are abstract and not quantifiable is challenging. Some of the regulations require certain properties in the model that people don't usually add, so	The interpretation of the building code is a challenge. Two major obstacles standing in the way are the lack of a formal digital representation of construction regulations and the

				the documents is one of the big inhibitors. The standards are gradually moved to XML format. Consistency is an issue when translating codes into computable forms. Quality assurance is needed to ensure the codes are correctly translated. The cross-check method has been used in code translations.		accumulated building permit data and model data can be used for smarter use. In Korea, the building codes and regulations are updated very frequently.	need to be further refined. Currently the regulations are manually digitalised into computer codes, in the future will explore automated code translation, which require more exploration in technologies.	lack of a method to automatically extract and transform information from construction regulatory documents into this computer-interpretable digital representation. The qualitative requirements are the key barrier of the ACC technology. Those rely on the human judgements.

Throughout its history, the global AEC industry has not been generally innovative, and there is much room for improvement (Blayse and Manley 2004). Many advanced construction markets like Singapore, Germany are facing challenges with declining productivity and low safety standards (Lim and Peltner 2011). As a result, it was observed from the global adoption of digital technologies that the government can play an important role at a macro level (**V1: Government support**). For example, an important lesson we can learn from the successful national deployment of BIM from Finland is that a national BIM strategy can facilitate the evolvement of the building and infrastructure sectors (Aksenova et al. 2019). The continuous government-led BIM adoption efforts in the UK, such as the BIM level 2 mandate, have helped the UK maintain a leader in implementing BIM on a national scale. The UK BIM standards (BS/PAS 1192 series) have now been accepted globally and have become ISO (International Organization for Standardization) standards (BSI 2018; ISO 2018). Similarly, the important role of the government can be found in facilitating the use of blockchain technology in the AEC industry (Perera et al. 2020).

For the adoption of ACC systems, a primary interest is to make the building consent/permit assessment easier, faster and more reliable. The BCA is a core end-user, but adopting ACC systems in this process will also directly benefit other stakeholders such as designers, and construction firms. The BCA could consider providing incentives (e.g. fast-track pathway, lower costs for building consent/permit assessment) to encourage, for example, designers to submit their applications in the required format (e.g. IFC). Simultaneously, policymakers can work out new guidelines and policy recommendations (e.g. new guidelines about preparing BIM-based e-submissions, new policies of ACC-based building consent procedures) to support this transformation. Additionally, Beach et al. (2020) pointed out that wide adoption of ACC requires the government to provide sufficient upfront investment and funding to support the research and development, pilot tests of ACC systems, case studies, and transformation of the whole AEC industry. Such funding will be paramount to influence small and medium enterprises (SMEs).

The AEC industry's innovations can be enhanced with sufficient support of the government (Suprun et al. 2021) (**V3: Industry readiness and innovativeness**). It can be learned from the UK experience that when the government proposes a national strategy of facilitating the adoption of BIM, stakeholders will tend to follow such a big move and benefit from consistent and common requirements and standards (Piroozfar et al. 2019). At the individual level, human resistance (people having a negative attitude towards accepting new technologies) has a negative influence on industry innovativeness (Mohd Ishak and Newton 2016) (**V2: Human resistance**). To address this issue, education and training provided through universities, industry associations, and other commercial institutions could help enhance knowledge and skills (**V4: Education and training**), which makes a positive contribution to innovative AEC industry. The analysis has led to the development of the following propositions (see also Figure 1):

Proposition 1a. Government support (through the means of funding, incentives and policy) has a positive effect on the innovativeness of the AEC industry, which increases the adoption of ACC systems.

Proposition 1b. Education and training have a positive effect on the innovativeness of the AEC industry, which increases the adoption of ACC systems.

Proposition 1c. Human resistance has a negative effect on the innovativeness of the AEC industry, which decreases the adoption of ACC systems.

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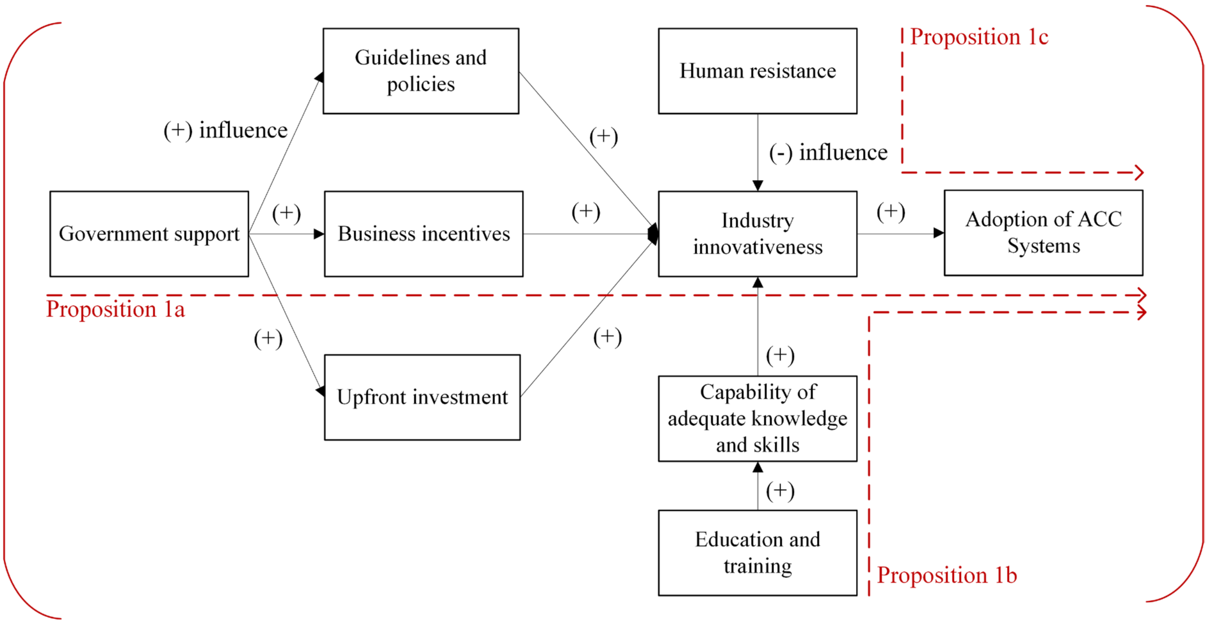

Figure 1. The first path explaining how growing innovativeness of the AEC industry leads to ACC adoption.

Tangible benefits of ACC systems can be proven through early stakeholder engagement and multiple pilot projects and case studies (**V7: Tangible benefits**). First, involving stakeholders from the early stage will ensure the real industry needs are addressed (**V5: Stakeholder engagement**). Once the technology is developed for real needs, stakeholders can see the benefits of the technology and will be more willing to accept it. Furthermore, pilot projects can be conducted on a small scale and tested for different sections of the building code (**V6: Pilot projects and case studies**). The main aims of such a pilot (Ciribini et al. 2016) will be (a) to test the new technology in solving real problems and gain experience for further technology improvement, (b) to gain implementation experience, (c) to validate the potential benefits of the new technology. More case studies are recommended to be conducted at this stage after the pilot projects. These efforts will help the AEC industry to gain more trust and confidence in adopting ACC systems. Meanwhile, an appropriate marketing function contributes to building stakeholders' trust and understanding (Yisa et al. 1996) (**V8: Appropriate marketing**). A common problem in current AEC industry is that marketing for new technologies trends to oversell and promise for functions that are not yet fully developed. The second path links the following propositions (see Figure 2):

Proposition 2a. Early stakeholder involvement has a positive effect on proving the benefits of ACC systems.

Proposition 2b. Conducting pilot projects and case studies has a positive effect on proving the benefits of ACC systems.

Proposition 2c. Tangible benefits and appropriate marketing strategy contribute to building stakeholders' trust and understanding, which has a positive effect on the adoption of ACC systems.

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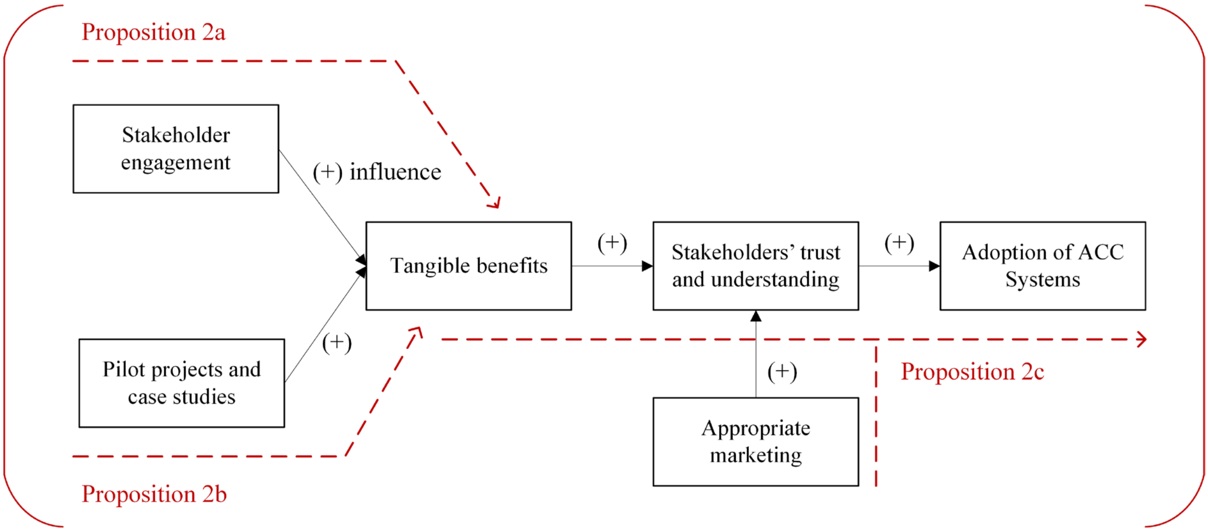

Figure 2. The second path model explaining how building stakeholders trust on ACC systems leads to adoption

The maturity of Industry 4.0 technologies, including ACC, is paramount for technology acceptance and adoption in construction (Oesterreich and Teuteberg 2016). Any insufficiency of ACC systems has a negative impact on its technology maturity. Four main paths were identified in this research that generate positive effects on improving the maturity of ACC systems. Firstly, the integration of ACC and other technologies has a positive effect on ACC maturity, through improved ease of use and data exchange (**V9: Technology integration**). For example, four main modules (Code checking module, Submission module, Pre-checking module, Automated rule-making module) have been integrated into the South Korean KBIM e-Submission system (Kim et al. 2020). End-users tested this system and their positive feedback on this integration included: (1) IFC-based submission set no requirement on specific BIM tools for designers, (2) the system improved collaboration through managing documents, project data and personnel information in a unified platform, (3) the automation of extracting input data from KBIM system reduced input time and increased accuracy of information. Secondly, due to the lack of modelling standards (Kong et al. 2020), BIM models are often generated in different ways by people in the building design process. The inconsistency in creating BIM models (e.g. naming objects between different software) will leave an issue for ACC to work. A BIM modelling standard that guides professionals on how to prepare the BIM models for ACC purposes can address this challenge (**V10: Modelling standards**). ACC will benefit from consistent and good-quality BIM models. In addition, such a standard can improve modelling quality and reduce efforts of fixing and enriching BIM models for ACC purposes. Thirdly, Amor and Dimyadi (2021) argued that the model for ACC to check should contain sufficient, correct and consistent information. Setting up a standard on information requirements (e.g. level of details, minimum data requirements) can lead to more accurate and better quality BIM for ACC purposes (**V11: Information standard and requirements**). Fourthly, paper-based building codes and standards are written in natural language by human experts and are published openly (Eastman et al. 2009).

To enable ACC to work, it is critical to create a computer-processable version of building codes. However, this interpretation of building codes is conducted by human experts, which is a time-consuming process. It showed from the NZ experience that it takes approximately a day of an expert's time to translate a page of a code and undertake quality control processes on the translation (Zou et al. 2022). Finding a standard approach to do the translation, and conducting quality assurance on the translation work will contribute to a good-quality and consistent digital version of building codes (**V12: Standard of interpreting building code**). Through analysing these insights and observations, the following propositions can be developed:

Proposition 3a. Integration of ACC and other systems contributes to improving the technology maturity, which has a positive effect on ACC adoption.

Proposition 3b. Development of a BIM modelling standard contributes to improving the technology maturity, which has a positive effect on ACC adoption.

Proposition 3c. Development of an information standard contributes to improving the technology maturity, which has a positive effect on ACC adoption.

Proposition 3d. Development of a standard for interpreting building codes contributes to improving the technology maturity, which has a positive effect on ACC adoption.

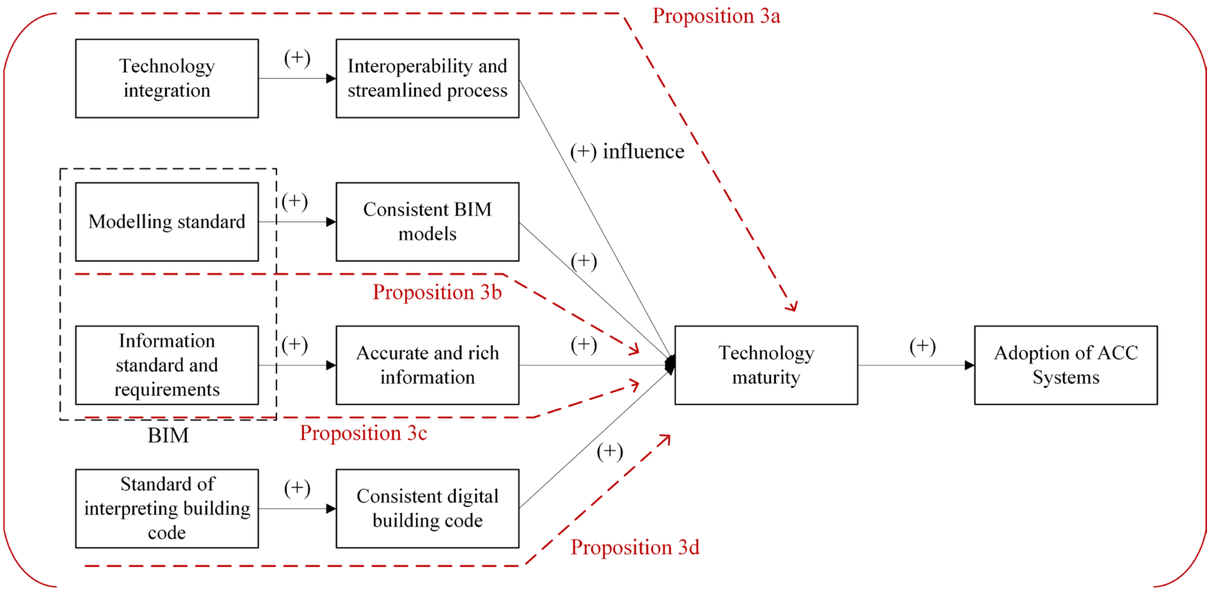

Figure 3. The third path model explaining the improvement of ACC maturity leads to adoption

Discussion

Contribution

The research outcomes contribute to the existing body of knowledge on ACC technology adoption from three aspects.

Firstly, many theoretical models, e.g., Technology Acceptance Model (Lee et al. 2003), and Technology, Organisation and Environment (TOE) framework (Dewi et al. 2018), have been developed to explain technology adoption process at both macro and micro levels. Most of these models are focused on high-level concepts and fail to illuminate details about adopting a specific technological innovation. For instance, TOE framework describes the process of adopting technological innovation is influence by technological, organizational and environmental contexts. However, it does not specify the factors that might exist in each context and explain the interaction of these factors. This study brings real-world lessons about ACC adoption experience from Australia, China, New Zealand, UK, Singapore, South Korea, Estonia and US, where 12 key variables and three path models that influence the adoption of ACC systems are identified. This multiple-case study is the world's first to investigate the adoption mechanisms of ACC systems in the AEC industry. By using ACC as example, it successfully demonstrates that interrelationships exist among key variables in technology adoption process and taking advantage of these interrelationships leads to better technology acceptance and adoption, thereby complementing existing technology adoption models (e.g., TOE framework).

Secondly, the research outcomes enriched our understanding on key variables that influence ACC adoption in the global AEC industries. Nearly all previous efforts (Dimyadi and Amor 2013; Eastman et al. 2009; Hjelseth 2015; Krijnen and Van Berlo 2016) that reviewed the ACC development and implementation were technology-focused. Beach et al. (2020) investigated ACC adoption in the UK but only focused on a single country. This paper reports a further-step study that extracts empirical lessons on ACC adoption from eight countries, finding 12 key variables (technology integration, BIM modelling standard, BIM information standard and requirements, and standard of interpreting building code, government support, human resistance, industry readiness and innovativeness, education and training, stakeholder engagement, pilot projects and case studies, tangible benefits, and appropriate marketing) that affect ACC adoption in all these countries and also providing many new insights in addition to the work by Beach et al. (2020). For instance, Beach et al. (2020) indicated that lacking artificial intelligence to interpret building code is a main barrier, while this study found it is more important to develop a standard approach to improve consistency of this interpretation. This study also highlights the importance of appropriate marketing as the ACC adoption is still at its early stage. Overselling or overpromising will lead to negative impacts on practitioners' trust on this technology. ACC needs to be further improved in terms of technical capability as well as be integrated into existing systems and workflows. Although the eight countries chose different digital technology adoption strategy (bottom-up approach or top-down approach), collaboration between academia, policymakers and the AEC industry is key.

Thirdly, the new path models developed in this research address the gap that no knowledge exists that can explain the interrelationships between key ACC adoption variables. Specifically, the first path reveals the importance of establishing an innovative AEC industry to facilitate the adoption of ACC systems. In this process, policymakers can play an important role through the means of funding, incentives and policy. According to the TOE framework (Dewi et al. 2018), it can be explained that the support from policymakers can catalyse an environment to adopt ACC. Adopting new technologies in AEC projects often benefits multiple stakeholders (Hall et al. 2013). Similar evidence on the importance of the policymakers' leading role can be observed from the adoption of BIM, blockchain, etc., (Aksenova et al. 2019; Perera et al. 2020). The first path also reflects improving education and training through tertiary and industry institutions has a positive effect on ACC adoption, which is in line with previous studies that investigated the relationship between innovation and education in the construction sector, e.g., Liu et al. (2010). The second path shows that building stakeholders' trust and understanding on ACC systems is a critical step towards adoption. The trend of overselling the benefits of new technologies in construction (Andresen et al. 2002) will harm trust. Early stakeholder engagement and conducting pilot projects and case studies will prove the benefits of ACC systems, thus bringing positive impacts on building trust. The third path reflects that improving the maturity of ACC systems can lead to adoption. Although previous studies (Amor and Dimyadi 2021; Eastman et al. 2009) already discussed the technical challenges (some are to be addressed in the next decades), this research found technology integration, BIM modelling standards, BIM information standards, and good-quality machine-readable building code are among the most important technical factors from a technology adoption perspective.

Management and policy implications

A number of management and pollical implications can be drawn based on the variables and path models.

Firstly, there are many ACC systems in the market; however, most of them have limited technical capabilities (Häußler et al. 2021). For instance, how to check qualitative statements has still not been fully addressed. An implication of this study for R&D managers in ACC technology firms is that the developed path models and propositions can support improving the adoption potential of their ACC systems in the market. From a technological perspective, they may collaborate with academics, legislative bodies and pilot users and consider improving the maturity of ACC systems through: (1)

enhancing the checking accuracy and consistency, and expanding ACC capacity to check more standards and requirements (e.g., qualitative statements of building code, urban planning and green building standards), (2) developing methods for checking the quality of BIM and semantically enriching BIM for ACC purpose, (3) extending ACC to check non-BIM formats (one possible way is through 2D drawing-based BIM reconstruction (Zhao et al. 2021)), (4) integration of systems and tools, and (5) developing a consistent, transparent and standard method of interpreting building code. From a non-technological perspective, obtaining end users' trust on using ACC systems needs a step-by-step strategy, including, e.g., engaging BCAs and pilot users throughout the whole process of developing ACC systems, conducting pilot tests and case studies, proving tangible benefits (not overselling).

Secondly, potential early adopters (e.g., BCA, architects, engineers) should investigate the state of practice of ACC systems, and develop their own adoption plans or roadmap to ensure the use of ACC systems will bring tangible benefits to their own businesses. There is also a need to balance the investment costs and expected benefits of adopting ACC systems.

Thirdly, it requires an innovative AEC sector to enable adoption of new technologies such as BIM and ACC. Tertiary institutions are important as they nurture AEC professionals for the next a few decades. Tertiary institutions and other education providers might consider: (1) transforming the existing curricula to meet new needs of digital technologies, (2) offering short courses to help practitioners understand how to prepare BIM models for ACC (e.g., BIM modelling recommendations, minimum information requirements), and how to use ACC to get satisfactory results. ACC technology firms might also support the education sector through offering education versions of ACC systems and co-training students with academics.

Fourthly, the case studies revealed that early collaboration between ACC technology firms, policymakers, industry associations and end-users is key to build stakeholders' trust in ACC and increase the acceptance and adoption of ACC systems in the early stages of market entry. Specific actions that require close collaboration include, e.g., (1) industry practitioners participating in ACC pilot tests, (2) BCAs, ACC technology firms and practitioners co-develop and co-maintain the digital format of building code.

Lastly, the case studies further show that the policymaker plays an important role to facilitate establishing an ACC uptake environment. From the policy perspectives, two main implications can be drawn from the results of this study.

- A major use case of ACC systems currently is to assist BCAs in assessing building consent applications, and make this process faster, easier and more transparent to both BCAs and building consent applicants. Our research indicates that the BCAs and policymakers should be open to BIM and ACC, and develop a timeline to adopt ACC systems. It is important to integrate ACC into existing building consent systems to help BCA officers better accept this new technology (Karlsson et al. 2010). Training and education can help BCA officers to become more familiar with the new technology and related software tools.
- The adoption of ACC for building consent assessment requires a systematic update of the whole process by all stakeholders. As an example, the BCAs' use of ACC will rely on information-rich, high-quality BIM models submitted by the building consent applicants. Jiang et al. (2022) categorised the government efforts of BIM adoption into two groups, i.e., top-down and bottom-up approaches. Since BIM is the precursor technology of ACC and the adoption of ACC is just emerging, Jiang et al. (2022)'s observation is applicable to the adoption of ACC at macro level (e.g., country). For countries where policies and regulations from central government are easy to implement, a government-driven approach for ACC adoption can be used, where appropriate. The policymakers might facilitate ACC adoption through long-term R&D and implementation funding for BIM and ACC, policies (e.g., mandate of BIM submission of public-funded projects), and incentives (e.g., fast-track pathway, lower costs for

building consent/permit assessment). For other countries like US (which is a federal union of 50 states and has many local state governments and different organisations working differently), a different way (e.g., industry-driven) may be adopted. For instance, the policymaker could play the key role as regulatory as well as support the establishment of alliances to guide the whole AEC industry to evolve.

Limitations and recommendations for future research

This research is not free of limitations. Firstly, the institutional contexts of the eight selected countries vary from one to another, because each country has unique characteristics in terms of policies, regulatory framework and approval processes, building typology, and stakeholder requirements, and so on. We focused on observing the homogeneity (i.e. the variables and path models that affect ACC adoption) across the eight countries; however, the impacts of institutional heterogeneity were not studied. Some researchers pointed out that institutional context can influence the diffusion of innovations (Papadonikolaki 2018; Tigabu et al. 2015). According to de Mello Brandão Vinholis et al. (2021), institutions refer to rules that frame and constrain economic behaviour and social interactions, where the macro-instructional level (e.g., country) is related to the regulatory environment. Some studies argued that the culture also matters in innovation adoption in the construction industry (Dorée 2004; Papadonikolaki 2018). In addition, UK and US are part of the Western World and share same western culture; however, UK adopted a top-down approach in BIM adoption (e.g. BIM mandate) while US adopted a bottom-up approach (Jiang et al. 2022). This might be explained that US is a federal system and its local states work differently in silos. It can be deduced that the political system might affect the adoption of innovation in AEC sector as well. So far, little is known on direct and indirect links between the institutional contexts and optimal ACC adoption pathways at macro level. As a result, further research is recommended to further explore the ACC adoption paths in these countries and analyse the impacts of institutional heterogeneity on ACC adoption from system perspectives.

Secondly, there is a large discrepancy in the level of ACC adoption between cases. For instance, the DesignCheck in Australia was developed around 2005 but was not used by the industry. The ePlanCheck in Singapore was used by the industry only for a few years in the beginning but remains as an active project commissioned by the Singapore government. Similarly, the KBIM system in Korea is actively being developed on a national level involving research institutions as well as the government. Since the adoption of ACC is just emerging (e.g., ACC has not been broadly used in most countries) and ACC is a very small field, we did not consider the maturity levels of ACC adoption in selected countries. Consequently, further research should consider developing maturity levels of ACC adoption and summarising adoption paths of ACC in each country.

Thirdly, twelve key variables and three path models were deduced. However, some case-specific features also existed and were not discussed in detail since it was not within the scope of this study. For instance, there are different opinions about whether the use of BIM and ACC should be mandated. Such a debate exists mostly because the AEC industry in each country has a different culture, market, political environment, etc. Future research is recommended to identify those case-specific variables and take a closer look at the comparison of different cases.

Conclusion

The increased momentum of ACC implementations in recent years has shown great potential in developing this technology for wider use to address real-world compliance checking issues. However, there has not been a dedicated ACC system today that has been adopted widely in construction, although there are fragmented software tools being used by industry's partitioners offering various degrees of compliance checking capabilities. To examine key variables and mechanisms that influence the adoption of ACC systems, this study conducted a multiple-case study. Valuable lessons have been learnt from the experience and the adoption efforts from eight different countries. Through cross-case analysis, four technology-related and eight non-technical key variables have been identified, and three path models have been deduced. The technology related variables include: (1) technology integration, (2) BIM modelling standard, (3) BIM information standard and requirements, and (4) standard of interpreting building code. Non-technical variables include: (1) government support, (2) human resistance, (3) industry readiness and innovativeness, (4) education and training, (5) stakeholder engagement, (6) pilot projects and case studies, (7) tangible benefits, (8) appropriate marketing. The path models reveal important interrelationships among these variables. Firstly, improving the innovativeness of the AEC industry through government support and proper training and education can lead to ACC adoption. Secondly, involving stakeholders and conducting case studies can prove the benefits of ACC systems. The proven benefits can help build the stakeholders' trust and understanding of this new technology, which leads to adoption. Thirdly, whether ACC has the capability of addressing real-world challenges is still a main concern of the end-users. Continuously improving the technology maturity and addressing any insufficiency of ACC systems can lead to wider adoption.

Data Availability Statement

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

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Appendix I. Interviewee profile

Interviewee No.	Profession	Country	ACC experience
A	Academic researcher	Australia	International leading ACC expert who was leading the development of an early ACC system in Australia.
B	Academic researcher	Australia	International leading ACC expert who was involved in the development of an early ACC system in Australia.
C	Designer	China	Design engineer who was involved in a major ACC pilot project in China.
D	BCA officer	China	BCA officer who was involved in a major ACC pilot project in China.
E	Academic researcher	China	Emerging researcher with >3 years ACC research experience.
F	ACC technologist	China	National leading ACC expert who was involved in the development of ACC software in China.
G	ACC technologist	Estonia	National leading ACC expert who was involved in the development of ACC software in Netherlands/Estonia.
H	ACC technologist	Estonia	National leading ACC expert who was involved in the development of ACC software in Netherlands/Estonia.
I	BCA officer	NZ	BCA officer who tested ACC systems and conducted a research

			project of ACC at master level
J	Standard expert	NZ	National leading standardisation expert
K	Standard expert	NZ	National leading standardisation expert
L	Academic researcher	NZ	International leading expert with >30 years ACC research experience
M	Academic researcher	Singapore	International leading expert who was recently involved in a major ACC development project in Singapore
N	ACC technologist	Singapore	International leading expert with >20 years ACC research and development experience
O	Academic researcher	South Korea	International leading expert with >14 years BIM/ACC research and development experience, who is involved in the development of KBIM ACC system
P	Academic researcher	South Korea	International leading expert with >20 years BIM/ACC research and development experience, who was leading the development of an earlier ACC system for Korea around 2010
Q	ACC technologist	South Korea	National leading ACC expert who is developing KBIM ACC system
R	Academic researcher	UK	International leading expert with >10 years ACC research and development experience
S	Construction expert	UK	Construction expert who had project experience (including substantial experience on building consent applications) in both UK and NZ
T	Academic researcher	US	International leading expert with >12 years BIM/ACC research experience, who has successfully commercialised his ACC research and is working closely with ACC technology firms
U	Academic researcher	US	International leading expert with >30 years ACC research experience, who has successfully commercialised his ACC research and is a founding member of an ACC technology firm in US

Notes: Two interviews involved two interviewees (G/H and J/K) each time; The interviews with interviewees P and Q were conducted via emails due to language/availability issues.

Appendix II. Path development

Supplementary data about the path development with supporting interview quotes and literature is provided in a separate MS Word file.

Reference

ABAB. 2019. "Australian BIM Strategic Framework." Australasian BIM Advisory Board (ABAB).

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

Amor, R., and Dimyadi, J. 2021. "The Promise of Automated Compliance Checking." *Developments in the Built Environment*. 5: 100039. https://doi.org/10.1016/j.dibe.2020.100039.

Andresen, J., Baldwin, A., Betts, M., Carter, C., Hamilton, A., Stokes, E., and Thorpe, T. 2002. "A framework for measuring IT innovation benefits." *Journal of Information Technology in Construction (ITcon)*. 5 (4): 57-72. https://www.itcon.org/2000/4.

BAC. 2017. "Three year report for the BIM Acceleration Committee." BIM Acceleration Committee (BAC).

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

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

Berends, L., and Johnston, J. 2005. "Using multiple coders to enhance qualitative analysis: The case of interviews with consumers of drug treatment." *Addiction Research & Theory*. 13 (4): 373-381. https://doi.org/10.1080/16066350500102237.

Blayse, A. M., and Manley, K. 2004. "Key influences on construction innovation." *Construction innovation*. 4 (3): 143-154. https://doi.org/10.1108/14714170410815060.

BSI. 2018. "PAS 1192-6:2018. Specification for collaborative sharing and use of structured Health and Safety information using BIM." British Standards Institution (BSI), London, UK.

buildingSMART Korea. 2022. "buildingSMART Korea Projects." Accessed 29 September 2022. https://www.buildingsmartkorea.org/work-projects-bim-research.

Built Offsite. 2017. "BIM Advisory Board Makes First Year." Accessed 29 September 2022. https://builtoffsite.com.au/emag/issue-08/bim-advisory-board-marks-first-year/.

CDBB. 2019. "D-COM: Digitisation of Requirements, Regulations and Compliance Checking Processes in the Built Environment." UK Centre for Digital Built Britain (CDBB).

Ciribini, A., Ventura, S. M., and Paneroni, M. 2016. "Implementation of an interoperable process to optimise design and construction phases of a residential building: A BIM Pilot Project." *Automation in Construction*. 71: 62-73. https://doi.org/10.1016/j.autcon.2016.03.005.

Clayton, M., Fudge, P., and Thompson, J. 2013. "Automated plan review for building code compliance using BIM." In *Proc., 20th International Workshop: Intelligent Computing in Engineering (EG-ICE 2013)*, 1-10. Munich, Germany: European Group for Intelligent Computing in Engineering (EG-ICE).

Cohen, J. 1960. "A coefficient of agreement for nominal scales." *Educational and psychological measurement*. 20 (1): 37-46.

Compliance Audit Systems Limited (CAS). 2019. "Case Study: Automated Compliance Audits." New Zealand National Science Challenge - Building Better Homes, Towns and Cities.

Construction Innovation Hub. 2022. "Construction Innovation Hub." Accessed 29 September 2022. https://constructioninnovationhub.org.uk/.

CRC Australia. 2005. "An advanced computer software tool that provides automated checking of designs against building codes." Australian Cooperative Research Centre (CRC) for Construction Innovation, Brisbane, Australia.

Creswell, J. W. 1999. "Chapter 18 - Mixed-Method Research: Introduction and Application." *Handbook of Educational Policy*, G. J. Cizek, ed., San Diego: Academic Press, 455-472.

de Mello Brandão Vinholis, M., Macchione Saes, M. S., Carrer, M. J., and Meirelles de Souza Filho, H. 2021. "The effect of meso-institutions on adoption of sustainable agricultural technology: A case study of the Brazilian Low Carbon Agriculture Plan." *Journal of Cleaner Production*. 280: 124334. https://doi.org/10.1016/j.jclepro.2020.124334.

Dewi, M. A. A., Hidayanto, A. N., Purwandari, B., Kosandi, M., and Budi, N. F. A. 2018. "Smart City Readiness Model Using Technology-Organization-Environment (TOE) Framework and Its Effect on Adoption Decision." In *Proc., 22nd Pacific Asia Conference on Information Systems (PACIS 2018)*, 268.

Dimyadi, J., and Amor, R. 2013. "Automated building code compliance checking. Where is it at?" In *Proc., CIB World Building Congress 2013*, 172-185. Brisbane, Australia: The International Council for Research and Innovation in Building and Construction (CIB).

Dimyadi, J., and Amor, R. 2017. "Automating Conventional Compliance Audit Processes." In *Proc., International Conference on Product Lifecycle Management*, 324-334. Seville, Spain: Springer.

Dimyadi, J., and Amor, R. 2019. "BIM-supported Compliance Verification of Performance-based Car-park Ventilation Design." In *Proc., the 4th International Conference on Civil and Building Engineering Informatics (ICCBEI)*, 259-265. Sendai, Japan: Asian Group for Civil Engineering Informatics (AGCEI).

Dimyadi, J., Fernando, S., Davies, K., and Amor, R. 2020. "Computerising the New Zealand Building Code for automated compliance audit." In *Proc., 6th New Zealand Built Environment Research Symposium (NZBERS)* 39-46.

Ding, L., Drogemuller, R., Rosenman, M., Marchant, D., and Gero, J. 2006. "Automating code checking for building designs-DesignCheck." *Clients Driving Construction Innovation: Moving Ideas into Practice*, K. Brown, K. Hampson, and P. Brandon, eds., Brisbane, Australia: Cooperative Research Centre for Construction Innovation, 113-126.

Dorée, A. G. 2004. "Collusion in the Dutch construction industry: An industrial organization perspective." *Building Research & Information*. 32 (2): 146-156. https://doi.org/10.1080/0961321032000172382.

Eastman, C., Lee, J.-m., Jeong, Y.-s., and Lee, J.-k. 2009. "Automatic rule-based checking of building designs." *Automation in construction*. 18 (8): 1011-1033. https://doi.org/10.1016/j.autcon.2009.07.002.

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

ECSO. 2020. "Policy fact sheet - The Estonian Digital Construction Cluster." European Construction Sector Observatory (ECSO), Brussels, Belgium.

Edhlund, B., and McDougall, A. 2019. *NVivo 12 essentials*, Stallarholmen, Sweden: Form & Kunskap AB.

Evans, W. 1996. "Computer-supported content analysis: Trends, tools, and techniques." *Social Science Computer Review*. 14 (3): 269-279. https://doi.org/10.1177/089443939601400302.

FIG. 2019. "Technical report - Introducing a Building Information Model (BIM)-based process for building permits in Estonia." Future Insight Group (FIG), Zwolle, Netherlands.

Georgiadou, M. C. 2019. "An overview of benefits and challenges of building information modelling (BIM) adoption in UK residential projects." *Construction Innovation*. 19 (3): 298-320. https://doi.org/10.1108/CI-04-2017-0030.

Gerring, J. 2017. *Case Study Research: Principles and Practices*, Cambridge, UK: Cambridge University Press.

Goh, B.-H. 2007. "E-Government for Construction: The Case of Singapore's CORENET Project." In *Proc., Research and Practical Issues of Enterprise Information Systems II*, 327-336. Boston, MA: Springer US.

Hall, P. V., O'Brien, T., and Woudsma, C. 2013. "Environmental innovation and the role of stakeholder collaboration in West Coast port gateways." *Research in Transportation Economics*. 42 (1): 87-96. https://doi.org/10.1016/j.retrec.2012.11.004.

Häußler, M., Esser, S., and Borrmann, A. 2021. "Code compliance checking of railway designs by integrating BIM, BPMN and DMN." *Automation in Construction*. 121: 103427. https://doi.org/10.1016/j.autcon.2020.103427.

Hjelseth, E. 2015. "BIM-based Model Checking (BMC)." *Building Information Modeling: Applications and Practices*, R. R. A. Issa, and S. Olbina, eds., Reston, Virginia: ASCE, 33-61.

HM Government. 2013. "Industrial Strategy: government and industry in partnership - Construction 2025." Her Majesty's (HM) Government, London, UK.

Hosseini, M. R., Banihashemi, S., Chileshe, N., Namzadi, M. O., Udeaja, C., Rameezdeen, R., and McCuen, T. 2016. "BIM adoption within Australian Small and Medium-sized Enterprises (SMEs): an innovation diffusion model." *Construction Economics and Building*. 16 (3): 71-86.

ISO. 2018. "ISO 19650-1:2018 Organization and digitization of information about buildings and civil engineering works, including building information modelling (BIM) — Information management using building information modelling — Part 1: Concepts and principles." International Organization for Standardization (ISO), Geneva, Switzerland.

Jiang, R., Wu, C., Lei, X., Shemery, A., Hampson, K. D., and Wu, P. 2022. "Government efforts and roadmaps for building information modeling implementation: lessons from Singapore, the UK and the US." *Engineering, Construction and Architectural Management*. 29 (2): 782-818. https://doi.org/10.1108/ECAM-08-2019-0438.

Karlsson, C., Taylor, M., and Taylor, A. 2010. "Integrating new technology in established organizations." *International Journal of Operations & Production Management*. 30 (7): 672-699. https://doi.org/10.1108/01443571011057290.

Khemlani, L. 2005. "CORENET e-PlanCheck: Singapore's automated code checking system." *AECbytes*, 1-8.

Kim, H., Lee, J.-K., Shin, J., and Choi, J. 2019. "Visual language approach to representing KBimCode-based Korea building code sentences for automated rule checking." *Journal of Computational Design and Engineering*. 6 (2): 143-148. https://doi.org/10.1016/j.jcde.2018.08.002.

Kim, I., Choi, J., Teo, E. A. L., and Sun, H. 2020. "Development of K-BIM e-Submission prototypical system for the openBIM-based building permit framework." *Journal of Civil Engineering and Management*. 26 (8): 744-756.

Kim, J. B., and Clayton, M. J. 2010. "Support Form-based Codes with Building Information Modeling–The Parametric Urban Model Case Study." In *Proc., 30th Annual Conference of the Association for Computer Aided Design in Architecture*, 133-138. New York, US: Association for Computer Aided Design in Architecture (ACADIA).

Kong, S. W. R., Lau, L. T., Wong, S. Y., and Phan, D. T. 2020. "A study on effectiveness of Building Information Modelling (BIM) on the Malaysian construction industry." In *Proc., 2nd Global Congress on Construction, Material and Structural Engineering*, 012035. Melaka, Malaysia: IOP Publishing.

Krijnen, T., and Van Berlo, L. 2016. "Methodologies for requirement checking on building models: a technology overview." In *Proc., 13th International Conference on Design and Decision Support Systems in Architecture and Urban Planning, DDSS 2016*, 1-11. Technische Universiteit Eindhoven.

Landis, J. R., and Koch, G. G. 1977. "The measurement of observer agreement for categorical data." *biometrics*: 159-174.

Lee, K., Park, Y.-h., Lee, G., Jung, W., Lee, S., and Lee, H. 2015. "An introduction to South Korea's BIM knowledge base development project." In *Proc., 32nd International Symposium on Automation and Robotics in Construction (ISARC)*, 1-5. Oulu, Finland: The International Association for Automation and Robotics in Construction (IAARC).

Lee, Y., Kozar, K. A., and Larsen, K. R. 2003. "The technology acceptance model: Past, present, and future." *Communications of the Association for information systems*. 12 (1): 50.

Lee, Y., Kozar, K. A., and Larsen, K. R. 2003. "The technology acceptance model: Past, present, and future." *Communications of the Association for information systems*. 12: 752-780. https://doi.org/10.17705/1cais.01250.

Liao, L., Teo Ai Lin, E., and Low, S. P. 2020. "Assessing building information modeling implementation readiness in building projects in Singapore." *Engineering, Construction and Architectural Management*. 27 (3): 700-724. https://doi.org/10.1108/ECAM-01-2019-0028.

Lim, J. N., and Peltner, F. 2011. "Innovation performance of construction enterprises." *Construction Innovation*. 11 (3): 282-304. https://doi.org/10.1108/14714171111149016.

Lincoln, Y. S., and Guba, E. G. 1985. *Naturalistic Inquiry*, Los Angeles, CA: SAGE Publications.

Liu, A., Hodgson, G., and Lord, W. 2010. "Innovation in construction education: The role of culture in e-learning." *Architectural Engineering and Design Management*. 6 (2): 91-102. https://doi.org/10.3763/aedm.2009.0109.

Liu, B., Wang, M., Zhang, Y., Liu, R., and Wang, A. 2017. "Review and Prospect of BIM Policy in China." In *Proc., World Multidisciplinary Civil Engineering-Architecture-Urban Planning Symposium (WMCAUS)*, 022021. Bristol, UK: IOP Publishing.

Ma, L., Lovreglio, R., Yi, W., Yiu, T. W., and Shan, M. 2022. "Barriers and strategies for building information modelling implementation: a comparative study between New Zealand and China." *International Journal of Construction Management*: 1-10. https://doi-org.ezproxy.auckland.ac.nz/10.1080/15623599.2022.2040076.

Miles, M. B., Huberman, A. M., and Saldaña, J. 2018. *Qualitative Data Analysis: A Methods Sourcebook*, Los Angeles, CA: SAGE Publications.

Mohd Ishak, S. S., and Newton, S. 2016. "An innovation resistance factor model." *Construction Economics and Building*. 16 (3): 87-103. http://dx.doi.org/10.5130/AJCEB.v16i3.5164.

Nanjing Government. 2021. "Nanjing issud the first BIM-based building consent within Jiangsu Province (南京发出全省首个 BIM 图审合格证)." Accessed 6 March 2022. http://www.nanjing.gov.cn/bmdt/202105/t20210520_2942552.html.

Nanjing Government. 2022. "Ministry of Housing and Urban-Rural Development promotes the BIM-based building consent system of Nanjing (南京市 BIM 审查和竣工验收备案系统获住建部推广)." Accessed 6 March 2022. http://www.nanjing.gov.cn/bmdt/202201/t20220114_3262742.html.

National Building Specification (NBS). 2014. "NBS pioneering automated checking of Building Regulations." Accessed 7 March 2022. https://www.thenbs.com/about-nbs/press-releases/nbs-pioneering-automated-checking-of-building-regulations.

NSC-BBHTC. 2019. "Automating compliance audits: Software pilot validates automated compliance checking against building standards." New Zealand National Science Challenge: Building Better Homes, Towns and Cities (NSC-BBHTC), Weillington, New Zealand.

O'Brien, B. 2021. "Zhang investigating BIM technology to automate building code compliance-checking, modular construction." Accessed 23 March 2022. https://polytechnic.purdue.edu/newsroom/zhang-investigating-bim-technology-automate-building-code-compliance-checking-modular.

Oesterreich, T. D., and Teuteberg, F. 2016. "Understanding the implications of digitisation and automation in the context of Industry 4.0: A triangulation approach and elements of a research agenda for the construction industry." *Computers in Industry*. 83: 121-139. https://doi.org/10.1016/j.compind.2016.09.006.

Palinkas, L. A., Horwitz, S. M., Green, C. A., Wisdom, J. P., Duan, N., and Hoagwood, K. 2015. "Purposeful Sampling for Qualitative Data Collection and Analysis in Mixed Method Implementation Research." *Adm Policy Ment Health*. 42 (5): 533-544. https://doi.org/10.1007/s10488-013-0528-y.

Papadonikolaki, E. 2018. "Loosely Coupled Systems of Innovation: Aligning BIM Adoption with Implementation in Dutch Construction." *Journal of Management in Engineering*. 34 (6): 05018009. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000644.

Perera, S., Nanayakkara, S., Rodrigo, M. N. N., Senaratne, S., and Weinand, R. 2020. "Blockchain technology: Is it hype or real in the construction industry?" *Journal of Industrial Information Integration*. 17: 100125. https://doi.org/10.1016/j.jii.2020.100125.

Piroozfar, P., Farr, E. R., Zadeh, A. H., Inacio, S. T., Kilgallon, S., and Jin, R. 2019. "Facilitating Building Information Modelling (BIM) using Integrated Project Delivery (IPD): A UK perspective." *Journal of Building Engineering*. 26: 100907. https://doi.org/10.1016/j.jobe.2019.100907.

Rowley, J. 2012. "Conducting Research Interviews." *Management Research Review*. 35 (3/4): 260-271. https://doi.org/10.1108/01409171211210154.

Saldaña, J. 2015. *The Coding Manual for Qualitative Researchers*, Los Angeles: CA: SAGE Publications.

Sari, K., and Bogdan, R. 1992. *Qualitative Research for Education: An Introduction to Theory and Methods*, Boston: Allyn and Bacon.

Shen, L., Edirisinghe, R., and Yang, M. 2016. "An investigation of BIM readiness of owners and facility managers in Singapore: Institutional case study." In *Proc., CIB World Building Congress (WBC) 2016*, 259-270. Tampere, Finland: The International Council for Research and Innovation in Building and Construction (CIB).

Soliman-Junior, J., Tzortzopoulos, P., and Kagioglou, M. 2022. "Designers' perspective on the use of automation to support regulatory compliance in healthcare building projects." *Construction Management and Economics*. 40 (2): 123-141. https://doi.org/10.1080/01446193.2021.2022176.

Sunström, E. 1999. "Should mothers work? Age and attitudes in Germany, Italy and Sweden." *International Journal of Social Welfare*. 8 (3): 193-205. https://doi.org/10.1111/1468-2397.00083.

Suprun, E., Stewart, R., Sahin, O., and Panuwatwanich, K. 2021. "Enhancing Innovativeness in the Construction Sector: A System Dynamics Analysis." In *Proc., 11th International Conference on Construction in the 21st Century*, 41-46. London, UK: Springer.

Tigabu, A. D., Berkhout, F., and van Beukering, P. 2015. "The diffusion of a renewable energy technology and innovation system functioning: Comparing bio-digestion in Kenya and Rwanda." *Technological Forecasting and Social Change*. 90: 331-345. https://doi.org/10.1016/j.techfore.2013.09.019.

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

UK BIM Task Group. 2011. "A report for the Government Construction Client Group - Building Information Modelling (BIM) Working Party Strategy Paper." Department for Business, Innovation and Skills, London, UK.

Wang, S., Liu, Z., Hao, Q., Zhao, Q., and Wu, X. 2021. "A survey on the development of data-driven compliance checking and government's purchasing AI for compliance checking in China (全国数字化审图, 政府购买服务人工智能 (AI) 审图情况的调研报告)." *China Engineering & Consulting*. 2: 68-79.

Ward, C. 2014. "BCAider." Accessed 6 March 2022. https://csiropedia.csiro.au/bcaider/.

Yin, R. K. 2011. *Applications of case study research*, SAGE.

Yin, R. K. 2013. "Validity and generalization in future case study evaluations." *Evaluation*. 19 (3): 321-332. https://doi.org/10.1177/1356389013497081.

Yisa, S. B., Ndekugri, I., and Ambrose, B. 1996. "A review of changes in the UK construction industry." *European Journal of Marketing*. 30 (3): 47-64. https://doi.org/10.1108/03090569610107427.

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

Zhao, Y., Deng, X., and Lai, H. 2021. "Reconstructing BIM from 2D structural drawings for existing buildings." *Automation in Construction*. 128: 103750.

Zou, Y., Wu, Y., Guo, B. H. W., Papadonikolaki, E., Dimyadi, J., and Hung, S. N. 2022. "Investigating the New Zealand Offsite Manufacturing Industry's Readiness for Automated Compliance Checking." *Journal of Construction Engineering and Management*. 148 (12): 05022013. https://doi.org/10.1061/(ASCE)CO.1943-7862.0002384.