buildings

MDPI

*Article*

# Innovative Use of Low-Cost Digitisation for Smart Information Systems in Construction Projects

**Mostafa Babaeian Jelodar [1,*] and Feiya Shu [2]**

[1] School of Built Environment, Massey University, Auckland 0745, New Zealand
[2] Department of Built Environment Engineering, Auckland University of Technology, Auckland 1142, New Zealand; sophia@planworx.co.nz
* Correspondence: m.b.jelodar@massey.ac.nz

**Abstract:** The low-level application of digital tools and information systems in construction implies that many projects cannot meet modern requirements and standard of work of advanced industries. This study adopts a practical and diagnostic approach to identify key attributes and implementation processes of information systems in construction and logistics. To have triangulation of knowledge, a three-step methodology is adopted. Initially an exploratory analysis of previous literature is performed. Secondly a diagnostic analysis of IS applications in construction is achieved by case studies. Finally, expert interviews are performed to examine and consolidate the findings. The study illustrated practical and innovative applications of low-cost digital tools in IS development and created a framework for documentation of these discrete and mostly unshared practices. It is recommended that the construction sector should embrace more advance technologies to minimise human intervention and enhance real-time capabilities. The practicality of how different low-cost and off-the-shelf tools and digital platforms can be combined is discussed and demonstrated. The study provides a clear distinction for practitioners and academics as to what is being practiced in comparison to the dominant theories.

**Keywords:** construction management; information systems; digitisation; smart construction; industry 4.0; building information modelling; project tracking; logistics

check for updates

**Citation:** Babaeian Jelodar, M.; Shu, F. Innovative Use of Low-Cost Digitisation for Smart Information Systems in Construction Projects. *Buildings* **2021**, *11*, 270. https://doi.org/10.3390/buildings11070270

Academic Editors: David J. Edwards, Clinton Aigbavboa, Obuks Ejohwomu and Chris Roberts

Received: 22 May 2021
Accepted: 16 June 2021
Published: 24 June 2021



## 1. Introduction

The construction industry is slow to pick up the digital tools and there are minimal support and training for new technological uptakes [1]. The pre-career training and tertiary education has not adopted digitisation and technology advances to its full potential. Construction practitioners are not receiving the required exposure to digital platforms and tool [2,3]. The smaller organisations which happen to constitute the larger percentage of the industry do not have the resources and money to utilise these technologies, and are often the end users of innovative products and generally are not innovators themselves [4,5]. The use of technology and the innovation model seem to change from one organisation to another, where size of the organisation is a significant contributing factor; and a substantial digital divide exists [6]. However, a common ground amongst all construction organisations regardless of their size is the need to manage and structure data and information via application of information systems (IS) in day-to-day practices. These systems are ever increasingly digitised in the modern era [7]. For instance, tools or systems such as building information modelling (BIM) and integrated design processes, semantic web-based information management system, Internet of Things (IoT), and sensors have been applied and popularised in construction [8,9].

The effective application of new technologies and digitisation is extremely important in times of uncertainty such as the recent global COVID-19 pandemic. In these circumstances where limitations are imposed, the smaller organisations become extremely vulnerable. Technology, digitisation and development of practical low-cost IS can facilitate construction activities and restore some of the reduced productivity [10,11]. Specially where there is significant differences between what researchers and digital developers recommend and what is actually happening within different projects [12]. Due to the lack of expertise and relatively low-tech nature of the industry the cost of IS application and innovation is very high and practitioners diverge from the intended application of digital tools [5]. These tools are often not accessible to greater proportion of the industry participants who are small to medium size enterprises (SME) with limited resources and financial capabilities [12]. Therefore, this study is a practical and diagnostic approach within digitisation capability and support for IS development in construction projects. The aim is to analyse the implementation of digital tools and technologies used to support IS in actual construction projects. The focus will be on providing recommendations for accessible and low-cost digital and technological support for IS development in construction.

## 2. Digitisation and Information Systems in Construction

The development of new technologies and digitisation can enable a holistic and systematic approach in governance and achievement of construction project goals. Information systems are being applied to strengthen the bond between people, equipment, and material. IS are generally regarded as systems for gathering, processing; possibly storing and disseminating information and outcomes [13]. It is important to understand IS in its own context and also IS enablers which could be different digital tools and technologies [12]. According to O'Hara, Watson [14] technology can be a component of IS or a tool to facilitate the functionality of these systems. The digitisation of IS and application of technology is being widely pursued in line with the Industrial Revolution 4.0 in construction. The aim of IS application in construction is to facilitate information exchange between parties at the right time and avoid many traditional quality issues caused by information deficiencies [15].

However, clarifications are required and digitisation should not be mistaken for IS; digitisation has a transformational effect on different information management processes and systems [16]. The oxford dictionary defines digitisation as "the conversion of text, pictures, or sound into a digital form that can be processed by a computer". Digitisation is perceived to be the key to further advancements in construction IS application. The process of digitisation requires technical expertise and is often too expensive for the average construction organisation [12]. Instead, IS are referred to as a network of hardware, software and technology used to collect, process, create and disseminate information and data [17]. Traditionally technology is regarded as an aspect of information systems alongside people tasks and structure. However, this aspect is now becoming a more dominant force in design and development of different information systems specially in the construction sector where the possibilities of new technologies are slowly being realised. In recent years the application and integration of new technologies and tools such as augmented reality (AR) on BIM platforms have been investigated [18]. With the advancement of knowledge transfer and capabilities of BIM, integrated project delivery systems have also been enhanced [19]. However, the formation of models and data collection is still largely manual and autonomies or real-time data entry is challenging. BIM is a popular IS platform often attracting new applications [3], which has influenced the digitisation process and added real-time and even dynamic modelling capabilities to construction processes [9]. The dominance of BIM as information system and management tool is so intense that other by-products such as BIM-based construction networks (BbCNs) has been introduced to enhance professional capabilities of the teams in carrying out projects tasks [20]. Also, with the improvement of digitisation capabilities in tracking and transportation, general construction logistics has also improved in recent years [21,22].

This clearly shows new technologies and digitisation are the antecedents of future advanced and practical IS for construction. Therefore, the two concepts of "digitisation" and "IS" must not be confused. While the goal of digitisation is to assist the application of different technologies and also facilitate use of IS in construction; it is well documented that the goal of IS in construction is to enhance productivity by efficient and timely management of data [9,11]. It was also demonstrated that IS and technological uptake is to improve quality. This is done through problem identification, communicating, documenting, responding, and providing effective and timely solutions [23–25].

Different digital and IS related knowledge areas are being explored, and attempts have been made in conceptualising the body of knowledge [2,26]. Advances in digitisation allows for real-time applications and usage of IS for execution of project tasks and operations [27,28]. However, the practicalities, improvisations, innovation processes and actual application of different emerging technologies are not often captured in previous research and furthermore these experiences are not being documented and shared. There has also been attempts at institutionalising best practices for certain technological advancements. However, the construction sector is not effective in institutionalising innovation, development of new technologies; and borrowing new concepts, compared to other sectors [12]. A case study approach and documentation of how different organisations apply and utilise digital technology and tools for IS development is be extremely beneficial.

## 3. Methodology

The issue of IS implementation is generally unstructured by nature and requires a diagnostic approach with some form of process tracking and evaluation over time. The study is looking at an innovative and evolving concept such as technology application which is a contemporary phenomenon in construction knowledge area. In addition, the study cannot use historically recorded data, due to its lack of existence [12]. According to Yin [29] case study oriented research is a good fit for this kind of research which does not necessarily follow conventional patterns. However, to make the study robust with descriptive power a three-step mixed methodology is designed and implemented. This provides different sources of evidence, means of validation and explanatory power; creating a valid and detailed classification for IS implementation [30,31]. The mixed method approach and combining knowledge sources is a popular way of providing detail, depth and validity for such unstructured knowledge areas [16,32]. The three steps are explained in this section.

### *3.1. Step 1. Theory and Conceptualisation*

A literature search is performed to explore what is currently being used and practiced, in the space of IS, communication, tracking and sensor technologies for the construction and logistics process. This stage also provides structure; and assists the formulation of the case study stage plus strategies for the interview questions in step three [33]. The search is conducted within reputable construction engineering and management sources. The aim is to identify frequently used IS, digital systems and their application trends within construction projects. This was the foundation for further diagnostic analysis to facilitate the application of digital IS. Additionally, IS application in construction logistics was also explored.

### *3.2. Step 2. Case Study*

Based on the exploratory nature of the study a comparative approach was adopted and four different cases were selected. This was to create an in-depth knowledge base and maximise generalisability power for the application and practice of IS in construction. This includes the study of IS application in project and logistics management cases. Historically these cases are highly contextual and boundaries between phenomenon and context are blurred. These case studies will provide more data and specific details on implementing IS which is difficult to capture through other means of data collection [29]. The approach has been applied to similar investigations on application of digital tools and technologies in different fields [32,34]. The cases were selected based on providing complementary information on the research question and aim of the study. A case study framework was formulated for the four cases and data required, as demonstrated in Figure 1. The framework demonstrates the information collected from each case study to make a meaningful comparison. This is a well-established selection and execution method in case study design [29].

The case studies were chosen to identify the common digital tools used in construction and logistics. In addition, information regarding the actual project, its context, benefits and functions of digital tools use, and specification of these tools were recorded and classified as common comparable information amongst the cases (Figure 1). Document reviews and publicly available information was mainly used as inputs to the case studies. Participation consent was achieved for more detailed information. A further comparison of the data and information obtained through the cases is performed to enrich the discussions on tools and applications.

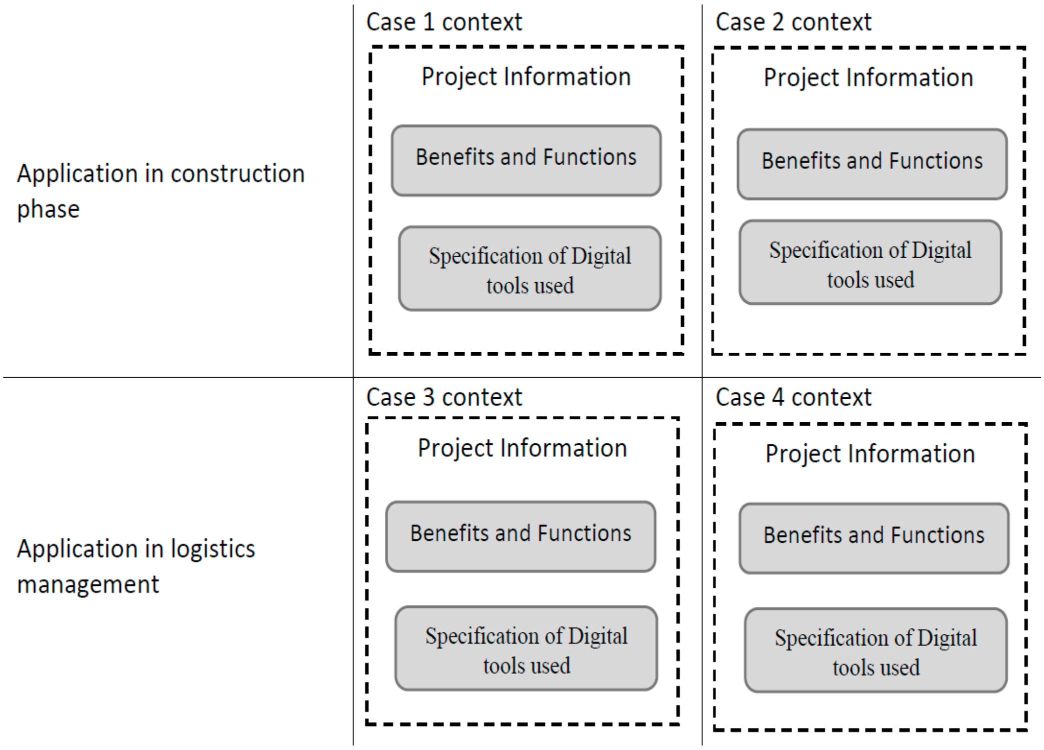


**Figure 1.** Case study framework developed based on Yin [29].

*3.3. Step Three. Semi-Structured Interviews*

As a complement and essential component of this study expert interviews were also performed. This is often used in such exploratory studies to provide more explanatory power and enable detailed discussion and analysis; which also serves as a measure of validity for the study [35,36]. The interview questions were formulated based on the results of literature review and the case studies to collect information on IS usage in construction processes and logistics management. The questions were exhaustively structured with a main principle theme and further complementary questions to capture maximum comprehension without further interpretations by the investigators [37]. The interviewees were selected based on purposive sampling; by considering their expertise in the field. To avoid any bias, the interviews were a parallel measure to the actual case studies and none of the interviewees had any connections to the case studies in the previous step. The interviews were continued to the point of theoretical saturation [38]. The participants were senior construction experts who were also involved in construction and logistics process. The condition for their participation was expertise in the field and current application of IS and digital tools, otherwise they would not be able to answer the interview questions.

## 4. Theory and Conceptualisation

The literature was conceptualised based on thematic analysis. The results are included in Table 1, and initially classified based on "themes", derived and their "references". Accordingly, the ability to innovate and IS applications were also included in the table. This provided the framework of conducting the case studies and interviews in the following sections.

From the examination of literature, the major themes related with digital tools and IS research in construction was extracted and tabulated in the first column of Table 1. The timeline of these studies show that themes of these studies are changing in a faster pace and the intervals between these dominant themes have changed from decades to just few years. One of the main themes of IS application in construction is communication [34]. This involves using digitisation and IS in communication with suppliers, communication for design, and even communication between the workers in different trades [39]. This was often the focus of construction research generally in the 90 s and 80 s. The focus shifted towards productivity enhancement through application of IS in the 2000s.

The advancement of digital technologies is an innovation enabler and affects team formation and collaboration models; making a shift to virtual teams possible. Tasks can be performed with real-time input and monitoring of global experts, increasing the capacity and potential of the sector [40]. For instance, BIM platforms can aid design coordination meetings to manage, prepare, visualize, inspect, document, and query within design [41]. This was later followed by autonomous monitoring, health and safety through development of IS in construction (Table 1). Another application of IS includes quality assurance; for instance, combination of different systems such as indoor positioning technologies and BIM has enhance quality management, reduce paper based operations and created accurate and faster results [42].

**Table 1.** Classification of IS and technology literature in construction.

| Major Themes [1] | Ability to Innovate [2] | IS Application and Benefits [3] | Current Initiatives [4] |
|---|---|---|---|
| • Communication (late 80s and 90s)<br>• Productivity (form the 2000s).<br>• Recently, more work has been done on autonomous monitoring and fault detection (generally in the past decade in 2010s)<br>• Health and safety (generally in the past decade in 2010s)<br>• Quality assurance is still quite rudimentary in construction literature. | • Organizational structure,<br>• line of work, and type of projects<br>• Public and private sector<br>• Size of organizations<br>• Skills and infrastructure | • Communication of design<br>• Track, monitor and evaluate work progress<br>• Productivity enhancement, both at industry and project level<br>• Quality of work, code compliance and conformance<br>• Fault detection<br>• supply chain and logistics<br>• Documentation and lessons learned | • To regulate uses of digital tools in construction:<br>• Ethical and workplace considerations<br>• Health, safety and well being<br>• Training and education of advanced tools<br>• To create integration and enhance innovation:<br>• BIM formularization and advocation<br>• Use of IoT, 5 G, and artificial intelligence platforms<br>• Application of sensors and digital data capturing<br>• Policy and incentives to facilitate digitization |

References: [1] [10,42–46]; [2] [5,7,12,32,46]; [3] [10,11,27,34,39–42]; [4] [5,6,8,11,32,43,44,47–50].

As demonstrated in the second column of Table 1, the ability to innovate and use digital technologies in IS development is dependent on organisational factors such as structure size, skills and infrastructure available. It was also dependent on the type of work and the sector of the organisations involved [12,46]. From the findings of the literature it is apparent that the industry lacks a clear understanding of innovation [5,6]. There is also lack of awareness and formal curriculum education of construction industry participants. Disproportionate attention has been paid to concepts such as BIM, and digital tools without developing infrastructure and underlaying capabilities [12]. Synchronisation of information is also another big problem specially within the supply chain where parties lack capabilities to integrate information; missing out critical data [8]. Conversely, the industry has low profit margins and is comprised of many small to medium size enterprises (SMEs) which naturally effects risk sharing and innovative capabilities. Therefore, there is a need to demonstrate practical innovative tools and low-cost solutions as well as some high-end products. This will improve diversity of application and provoke further innovation amongst less financially capable parties.

More specific applications of IS and benefits were also documented in Table 1. This included communication of design; tracking, monitoring and evaluation of work progress; productivity enhancement, both at industry and project level; quality assurance and code compliance; fault detection; supply chain and logistics; documentation and lessons learned. Although these applications are studied, the practicalities and methods of implementations are not clear. There is lack of actual examples and cases illustrating these implementations. Accordingly, more recent issues such as ethics, health and safety and training were also identified as regulating factors in the application of digital tools in construction. Creating integration and enhancing innovation through BIM formularization and advocation; use of artificial intelligence with IoT and 5 G; application of sensors; digital data capturing; policy making and incentives to facilitate digitization are also within current research initiatives in construction (Column 4, Table 1).

## 5. Case Studies

In this section the results of the four construction case studies are categorized and presented. Table 2 presents a summary of the information for these cases.

**Table 2.** Summary of the four case studies.

| Case Studies | Project Information | Benefits and Functions Results | Specification | |
|---|---|---|---|---|
| Case 1: Mason Bros. Commercial Precinct | • Multi story building, Location Auckland New Zealand<br>• structural steel external bracing;<br>• Commercial zone has 5500 $m^2$ work area and a 3-storey rental area.<br>• Developed by External Consultant | Improve communication<br>Improve architectural design<br>Data visualization<br>3D modelling<br>Real-time data sharing | Covered area<br>Construction time<br>Information system<br>Improve communication<br>Improve architectural design<br>Data visualization<br>3D modelling<br>Share data real time<br>Display Problem Notification<br>Supervise processes | 5500 $m^2$<br>1.5 years<br>BIM 360Glue, BIM 360 Field & Building Ops.<br>√<br>√<br>√<br>√<br>√<br>×<br>× |
| Case2: Taikang Wuyuan rehabilitation hospital | • North of Tongxi, Huancheng road industrial park, Suzhou China<br>• The total proportion is about 9600 square meters.<br>• Total investment is 16 million dollars included environmental<br>• Developed by contractor in-house systems | Data visualization<br>Share data real time<br>Display Problem Notification<br>Supervise processes | Covered area<br>Construction time<br>Information system<br>Improve communication<br>Improve architectural design<br>Data visualization<br>3D modelling<br>Share data real time<br>Display Problem Notification<br>Supervise processes | 9600 $m^2$<br>1.3 years<br>IBMS, PaaS, and hosting multiple SaaS<br>√<br>×<br>√<br>×<br>√<br>√<br>√ |
| Case 3:Trimble's Westminster Campus building two | • New building located in Westminster, Colorado, USA.<br>• Mixed concrete frame with slabs<br>• Cover area 11,000 square-meters in four levels.<br>• The company is construction software and hardware provider | Ensure the quality of concrete<br>Improve communication<br>Delivered on time | Use of internal information system<br>Type of information system<br>Effective communication<br>Avoid material damage<br>Route planning automatic<br>Avoid delivery delay<br>High quality | √<br>TrimFleet suite<br>√<br>√<br>√<br>√<br>√ |
| Case 4: Material supply company (China) | • Supplier of foundation material, timber elements, floor systems<br>• Suppliers adaptation of technology | Logistics management<br>Generating invoices | Use of internal information system<br>Type of information system<br>Effective communication<br>Avoid material damage<br>Route planning automatic<br>Avoid delivery delay<br>High quality | ×<br>Hand-Held Terminals (HHT) and BtoB<br>×<br>×<br>×<br>×<br>× |

### *5.1. Case One*

Mason Bros. Building located on the edge of Waitemata Harbor (Auckland, New Zealand); is a commercial development zone with 5500 $m^2$ work area and a 3-storey rental area. Construction on the building started in November 2015 and was completed in mid-2017. Total duration of construction was around 18 months. The building was designed in line with the innovative redevelopment solutions of Auckland's Wynyard Quarter Innovation Precinct (WQIP) and sought an innovative redevelopment solution regarding sustainability and responsiveness to change. In addition, via the application of technology a fully integrated and specific asset information management (AIM) system was foreseen for maximum efficiency of operations, and capital costs expenditure for this building [51].

The digital capture of information for the building's assets began during the construction process with an external consultant training the contractor and the supply chain on how to create a digital database; as the basis for a complete "digital handover". The IS solution created involved Autodesk software such as BIM 360Glue, BIM 360 Field and Building Ops to capture information generated in construction and link to an asset management cloud database. The system enabled data entry through both mobile devices and a web browser interface. The system has imbedded abilities such as downloading 3D models and relevant data on mobile devices, in addition to uploading commissioning documents and operation manuals.

In this system, 3D models, documents and data are stored in a central repository. The information exchange is transparent; and could be accessed by authorised individuals involved at any time. Accordingly, the uploaded construction data and progress information can be rapidly and clearly displayed on a digital dashboard. Tableau was used for the digital dashboards and a real-time demonstration of the data captured in BIM 360 Field. This was a real-time user-friendly IS setup for workflow management and communication based on BIM; planned in construction phase to facilitate capturing asset information. The IS set-up for this case not only increased productivity; it also provided architects with modelling capabilities. They were able to explore different ideas and identify potential design problems lending to significant reduction in errors and improving overall quality.

On the other hand, this project applied construction mobile technology to capture ongoing asset management and critical building information. This mobility and digitalization of data increased the speed of information exchange and added extra versatility of applications and analysis. Accordingly, the IS consultant was able to disseminate detailed, up-to-date and reliable information on equipment use. Another benefit of the system is the access of project team to 3D models and other building information real-time through mobile devices during and post construction phase. Overall, this. Apart from enhancing work orders and monitoring construction quality in real-time, the system can also be used to manage hazards, emergencies, and even planning during disaster recovery situations.

### *5.2. Case Two*

Suzhou Taikang Wuyuan rehabilitation hospital is a new building project located in Suzhou (China). The total project investment was $16 million dollars included environmental protection investment of about $700,000 dollars. The total covered building area is about 9600 square meters. The project consists of two large core buildings identified as buildings three and four respectively covering 1287 $m^2$ and 8306 $m^2$ of total floor area. The functional area in these buildings contained examination room, X-ray room, and department of stomatology, outpatient surgical centre and surgical ward.

A specific IS was developed for this project through interconnections within company resources and called the intelligent building management system (IBMS). The system had the goal of coordination between subsystems in use, optimising their interactions through real-time links to other systems, and providing history and updated reports. The resulting functions as a digital and information support platform; included collecting status information from each subsystem, automated monitoring of key equipment and providing real-time data for cloud computing whether platform-as-a-service (PaaS) or software-as-a-service (SaaS). This system also provides operation support post construction to firefighting facilities, security system, etc.

The project was complex involving many subsystems components and teams; which required communication, information sharing and integration to run efficiently. Hence the developed IBMS on the cloud computing PaaS was used to capture, analyse and communicate information through its various imbedded services and applications. All design specifications, engineering information, work requirements and processes were covered by the cloud platform, in order to keep the staff informed and updated with latest developments. The PaaS provides the platform and background support for multiple SaaS. The role of SaaS in the system is to create modules of data for the information to be distributed, demonstrated and managed by mobile devices. The mobile APP interface supported by IBMS is shown in Figure 2.

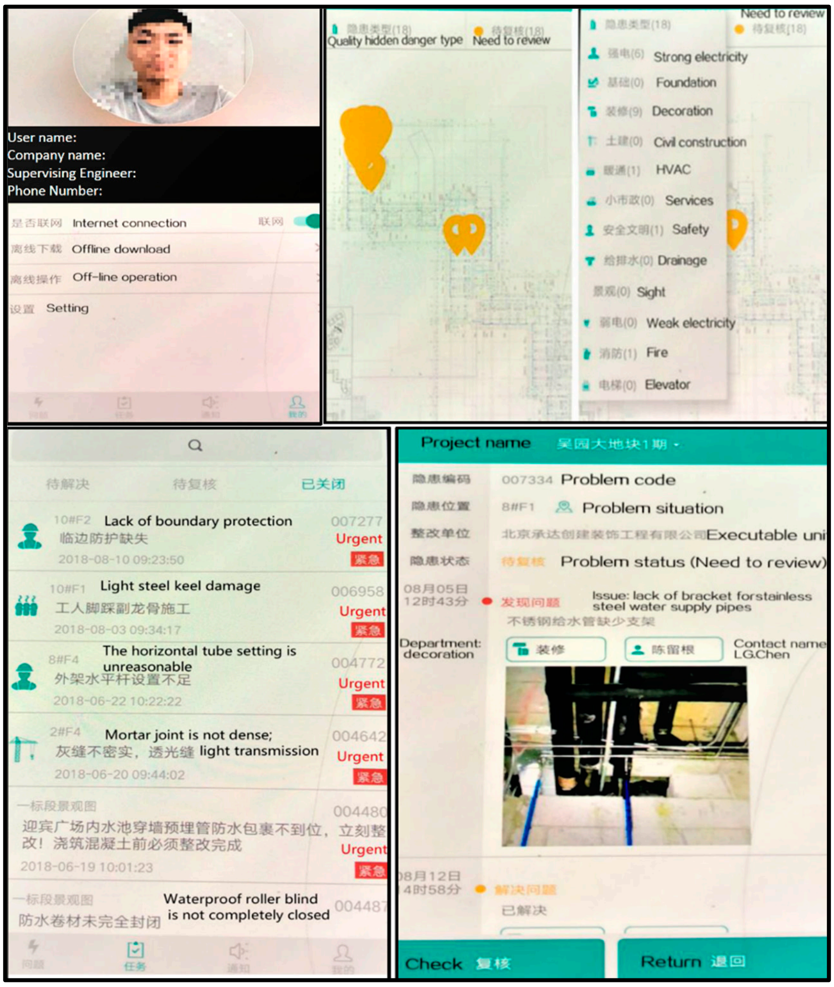


**Figure 2.** Mobile application interface of the developed IBMS (**top left**); demonstrating real-time data capture (**top right**); problem log (**bottom left**); inspection and reporting (**bottom right**).

Each staff member has real-time access to project information; and the project manager can monitor the progress of different sections and stages. The developed IBMS allows the project leader to monitor and scan various information (positive or negative) of the project in a timely manner (Figure 2 bottom right); enhancing understanding of the actual project status. Furthermore, the system encourages team collaboration, supervision, inspection, and assessments through a real-time dynamic management tool for the work performed by different crews and project departments.

Figure 2 (bottom right) illustrates the reporting and systematic input capabilities of a problem found by one of the staff supervisors. The input was almost immediate through the mobile app onsite. The depositing of information was done by a picture taken from the situation, followed by coding the problem and escalating the issue. A brief description of the problem was provided to the parties responsible and main decision makers. This function replaces the traditional close-up inspection processes and face-to-face meetings by providing necessary information for decision-making in a relatively short amount of time.

In addition, the research and development personnel for this IBMS developed an automated scheduling tool based on inputs from engineering quantities, work breakdown structure, technical quality standards, and progress reports. The tool can specify and demonstrate critical path and finds real-time alternatives in case of variations and change orders. This enabled a real-time and automated progress monitoring tool, which could propose daily, weekly, monthly and even longer-term amendments to the schedule instantly. Routine progress evaluation becomes less labour intensive and are performed timely based on data received. The IBMS also facilitates management of construction project processes including contract delivery, cost management, equipment management, etc. Managing all these processes by a main central system created by PaaS/SaaS reduces the possibility of misplaced information, double recording of data, and prevents unnecessary non-value adding activities. This results in higher quality more efficient final construction product in potentially a shorter period.

### 5.3. Case Study Three

Trimble's Westminster Campus building is a new mixed concrete frame building located in Westminster (CO, USA). The building cover area was 11,000 square-meters in four levels which could place around 650 employees. Construction duration was 15 months and completed in late 2018. TrimFleet Suit was used as an in-house developed technology by the Trimble company called for logistics management. The purpose was to streamline operations as well as coordinate work through the building workflow. TrimFleet Suite is a tool designed specifically for the construction materials providers. Concrete was the main material used, so Trimble drum rotation sensors were installed on concrete delivery trucks and the hardware kit was installed in the conveyance to provide real-time location and status information for drivers. The software used in mobile application and personal computer help manage the product delivery cycle by showing dispatchers location and status data on each vehicle in real-time. This suite included the following IS:

- TrimView system: Reporting, mapping and message
- TrimView Data Base: Provide data and analytics
- Information exchange system: Integrating information with third party Enterprise Resource Planning (ERP) systems

This system solves common problems during material transportation ranging from maintaining the standard quality, delay and delivery issues. The tracker application within TrimFleet monitors all the vehicles and their tracks to ensure the process of logistics runs smooth. The drum rotation sensor measures speed direction and rotation count of the mixer drum. There is a water-added meter in this sensor used to measure the amount of water added before and during the water flow to ensure material quality meets the code requirements specified by the client. Furthermore, the data will be stored in TrimView database where it is easy to retrieve and manage by the client.

The system also provides communication capabilities between construction site and trucks in real-time. For example, in an instance where the drill had hit hard on the bedrock during the construction process the foundation depth could not be achieved by the time anticipated to match the calculated concrete preparation time. The TrimFleet functions allowed material dispatchers to communicate with general contractor as soon as the problem occurred; then operators could determine when the right foundation depths were reached and when concrete should be shipped to construction site by trucks. Without the system the concrete would be dispatched regardless of these issues, which meant losing its quality, and requiring additional remedial work before pouring. The system also was equipped with GPS and could provide the drivers and operators with real-time traffic and weather conditions.

### 5.4. Case Study Four

A material supplier specialising in construction material that offers a wide selection of products such as foundation materials, timber elements and floor systems in China. However, the company's logistical practices were conventional, lending to problems; especially in managing supply chains. One of the main problems with their operations was the data capturing process; where important information such as material weight and volume was not appropriately recorded. The lack of attention to product information affects the loading plans, causing overloading or improper material stacking leading to material damage. Not controlling the delivery time and specific volume of products according to both the customer requirements and product characteristics, resulted in a random delivery method. In addition, the trucks were not equipped with a smart navigation system leading to delays and logistical issues.

Another problem was communication and transfer of information to other branches. There was lack of information standardization and each store had individual operation procedures; making information sharing with other branches and headquarters ineffective. Due to delayed orders and inaccurate information, some branches were out of stock while others had material stacked for long periods of time leading to spoilage and quality issues.

This adversely affected the business and the company lost many customers, which triggered changes in both organisation and logistics strategy. Use of IS was suggested and initially simple hand-held terminals (HHT) was utilised for inventory dispatching, tracking and management. This significantly improved accuracy and made the loading plan easier and safer to manage.

The application of HHT also optimised storage and inventory times which led to better preservation. Realising the value of digitisation, the company decided to adopt B-to-B; an electronic information platform to improve communication with clients, partners and suppliers. However, the application of these tools is still preliminary and discrete; more integration and systematic approach is required to realise its maximum potential. In-house IT experts and systems are required to make the whole fleet and supply chain compatible with inventory capacity and delivery capability. The stores' branches, inventories, vehicles, and other assets must be controlled and managed in a digital and dynamic network; facilitated by input terminals and sensors. Accordingly, the company can reduce human intervention and errors by increasing digital infrastructure and automation. Moreover, an open source system can have the ability to host different input data and integrate multiple information systems. A summary of the four case studies is included in Table 2 which will be discussed in the next section.

## 6. Discussion

In this section the results from the case studies and interviews are analysed and compared with previous literature to provide triangulation of knowledge.

### 6.1. Case Study Discussion

The initial comparison of the four cases indicates different forms and levels of IS and technology applications in construction by different parties and stakeholders. The summary of the four cases are included in Table 2. The IS developed by external consultants are usually more sophisticated and have greater compatibility with a multitude of applications for different phases.

As demonstrated in the Taikang Wuyuan rehabilitation hospitals' case; the IS was focused on combination of software and capabilities of PaaS and SaaS. However, for the Trimble's Westminster Campus building two the IS was based on hardware and their TrimFleet Suite. The functionality of the IS includes improving communication, real-time information sharing, data visualisation, 3D modelling, design, problem notification; supervision; logistics; inventory management; fleet management; generating reports and invoices. Although there is value in the systems for quality; there is hardly any systematic approaches for quality assurance. The code compliance process or material standards are not well integrated into these processes and only discrete problem detection are conducted as demonstrated in case 2. Currently the construction industry is missing out on the potential of automated processes and integrated quality assurance mechanisms due to the lack of IT and technological expertise amongst practitioners. What makes this more unfortunate is that the current infrastructure and IS have the capability to host these systems; and significant reinvestment in new systems may not be required.

Cases one and two have similar systems but developed by different parties. The IS in case one Mason Bros. commercial precinct is created based on clients' requests by an external consultant for the purpose of easier asset control, maintained and operations. However, case two is an internal IS created by contractor to serve the purpose of construction phase only. Table 2 displays the impacts of these different IS.

Both systems enable real-time data sharing and visualization, therefore the time of information transmission in the both projects are shortened by using IS. IBMS in cases 2 does not have the automatic 3D modelling capability and requires more human intervention and time for completion of design process; which may lead to more design errors. The absence of this capability may result in quality issues. However, there are two unique properties in IBMS which allows problem notifications and remote supervision. Accordingly, quality issues during on-site construction can be discovered and resolved in time. By comparing cases 1 and 2; it becomes apparent that the IS driven by BIM and IBMS, both can solve the communication problems in construction projects. BIM can bring more convenience during the design phase and reduce the possible design mistakes. The benefits of IBMS are apparent in on-site construction process. Noticeably different IS are used for diversifying quality benefits and IS selection should be according to project and construction conditions. This can speed up the flow of information and improve building quality issues caused by inaccurate information or slow communication.

Through comparing cases 3 and 4, which mainly involve logistics management, it is apparent that these activities require IT products with specific hardware (Table 2). The suppliers and companies involved in construction logistics tend to buy off-the shelf products for managing their delivery's and inventories, rather than developing them from scratch. As illustrated companies such as Trimble are market providers of these systems for construction projects and material suppliers. Table 2 illustrates the application of IS in logistics management could solve many shortcomings of traditional logistics methods and improve overall construction quality. Features such as communication, material safety, routing and transformation time can be improved and optimised through these applications. Case 4 illustrates that logistics without IS does not address these issues and adversely affects construction quality.

### 6.2. Interview Discussion

A total of seven interviews were conducted to achieve theoretical saturation and gain more insight on application of innovative IS in construction. The interviewees were senior construction experts ranging from project management roles to engineers, consultants, logistics managers and CEO's of construction companies. The respondents all had experience of working with IS and new technologies. Results from the interviews were tabulated to create a knowledge map (Table 3).

Although some knowledge is available on IS application in construction management and logistics; there is not enough compelling insight to make industry practitioners adopt the state-of-the-art systems. Apart from general technicalities, the cost of software operation is high and requires regular updates of modules and skills. According to the experts the base of most construction IS currently in use are BIM integrated applications which can build different layers of information. The applications grow in sophistication with the increase in projects scale. More powerful clients such as the government or public agencies have their standard IS requirements which could be mandated for different projects. With some state-owned enterprises each department has its own IS requirement, for instance in the past decades some of these department only used CAD to design drawing.

**Table 3.** Knowledge map of the information obtained from interviews.

| | | |
|---|---|---|
| **Common Information Systems and Software Applications** | **Functions:**<br>Architectural Design and Integration,<br>Management of Projects and Resources<br>Supply Chain Management and Logistics | **Tools Used:**<br>Autodesk and CAD, BIM and IBMS,<br>Mobile Phones and Apps Social Media Networks (WeChat, WhatsApp) and Text Massages for Small Projects and Operation |
| **Quality improvement functions** | **Main requirements:**<br>Technical clarification<br>Tracking and monitoring capability<br>Documentation and record of technical data<br>Engineering features and quality requirements<br>Code compliance<br>Construction method and progress documentation<br>Health and Safety consideration<br>Real-time data sharing | **General practice and tools:**<br>Physical and Manual inspection of facilities<br>Manual data entry<br>Peer reviews based<br>External compliance checks<br>Use of CCTV and photogrammetry<br>Laser profiling |
| **Information systems for construction logistics** | **What is managed:**<br>Material warehouse<br>Material Transportation<br>Inventories<br>Weather conditions<br>Ordering, dispatching and storing<br>Quality controls and replenishment | **What dos industry use:**<br>Basic phone functions and massaging<br>Not very sophisticated systems as it requires significant training<br>Not really have an idea of different systems available and their benefits |
| **IS tools and technology used by logistics companies and large warehouses** | **What is managed and required:**<br>Mainly involves third parties<br>Often there is no integration with other process<br>The data is kept by the supplier and not passed on<br>The information is used for delivery and seldom used in quality control. | **Tools used**<br>Mainly accounting software to track both flow and also issue invoice.<br>With larger warehouses specific software and senor technology (RFID) is used to track, manage location, monitor stock and movement.<br>Freight Tracking (ICOS Live) involves real-time track and trace. It can show speed, location and time vehicles and fleet in action<br>Gearbox is used for fleet management, warning system and fleet safety.<br>Still use NCR books for documentation; the perception is that it allows more freedom on-site and is quite dynamic. |

The experts could identify some software used for architectural and design management purposes; however, their experience with information systems for quality improvement was little. For instance, technical clarifications are a requirement from the client side, but the IS available do not have specific designated application for such inquiries. This is while integrated design and cloud-based technology is facilitating direct communications and access to larger databases.

Another less developed area is the monitoring and tracking capabilities as an integrated application of IS platforms. The existing practice mainly involves manual inspections and entry of information; whilst technological capabilities such as application of sensor, image processing, thermal imaging, RFID and IoT can reduce human intervention and provide more reliable and real-time updates of project status. Other more conventional systems to collect information may include CCTV footage, laser profiling and photogrammetry which are generally independent assessment outputs with low IS integration.

Most of logistics and supply chain activities in construction are outsourced; unless there is a need for large material depot or storage and warehouse system, where the project team will generally work with suppliers on demand. Therefore, suppliers are the logistics professionals and end users of such IS technology. Some of these firms are traditional and use simple, phone applications, GPS and navigation tools whiles others use sophisticated off-the-shelf products from developers in the field. More sophisticated tools have functionalities such as material quality checks, optimum storage and delivery method, leading to less delays damage and waste.

Leading material providers use technology and software for layout management or use general account management software to track flow, storage, movement and dispatch of material. The type of IS used is dependent on warehouse size; as it is difficult to justify cost of more sophisticated tools for smaller warehouses. Software is used to track and trace both the consignments and the fleet. Freight tracking applications such as ICOS Live allows real-time location tracking of fleet. The system is accessible through PC or mobile device and can show speed, location and delivery time. Electronic Control Unit, Prestart and Gearbox applications have safety warning and documentation capabilities; however, current logistics documentation is still largely with no carbon required (NCR) books (Table 3). This suits the less technologically informed and allow more freedom onsite in dynamic situations.

## 7. Conclusions

By performing a diagnostic analysis through literature review and multiple case studies it is demonstrated that a significant proportion of IS use and digitisation in construction is due to innovation and capabilities of the applying organisation. The study found that only the larger organisations with different levels of experts and resources could develop such innovative capabilities. However, there are low-cost technologies which the industry should be aware of and trainings should be conducted for these applications. Case studies 2 and 4, summarised in Table 2, clearly demonstrate the awareness of these low-cost technologies and their application can significantly improve the ability to innovate and digitise IS to the benefit of construction parties.

This study revealed that due to extremely multidisciplinary nature of modern construction; the industry has started its own quests and experimentation with new technologies to spark innovation and digitisation. For instance, BIM based applications have enhanced multidisciplinary collaborations through the virtues of integrated design. This has been documented in multiple other sources and article, where many different tools, technologies and processes have been proposed and developed in compatibility with BIM [11,19,21,41,46]. BIM has almost become a prescriptive platform for innovation and digitisation in construction. However, there could be other means of innovation as demonstrated in case study two which may not need as much preparation, resources, time and cost.

The study illustrates innovative use of IS and digitisation by different parties involved which are often discrete efforts and not shared with other industry experts and academia. This lack of knowledge sharing is extremely prohibiting further advancements especially in IS and digitisation in construction. This is evident from the result of the expert interviews and demonstrated through the case studies. According to findings of this study there is a disproportionality of themes in relation to the application of information systems, new technology and digitisation in construction (Table 1). The sector is losing out on integrated information systems and platforms which could capture critical data in correspondence to communication, productivity, quality and logistics. This prohibits the construction industry form creating a holistic and detailed digital map of construction processes, resulting in many functions manually carried out.

This study explores the more practical aspects of IS and digitisation in the construction sector; emphasising on actual methods of application and innovation. This is a clear illustration of what is being practiced in comparison to the available theories. Although there is high capacity and potential for digitisation, the capacity has not been built in the average construction firm and the real potential has not been realised, as illustrated in case one. The construction practitioners should initially identify and classify the common tools and technologies being used in different construction projects. It is important to identify what is available locally and potentially at a cheaper rate and what is available globally. In accordance, the benefits of applying these systems should be weighed against the costs of current practices. A classification of low-cost to high-cost IS and digital tools can be achieved. The industry practitioners should experiment and combine different tools and technologies as illustrated in the case studies to customise their own IS work settings and platforms. The application of more tools and technologies can create a foundation for further combinations, innovative applications and development of IS. The industry should embrace the potentials of new technologies such as use of sensors, image processing, thermal imaging, RFID, CCTV footage, laser profiling, photogrammetry and IoT to reduce human intervention and enhance real-time capabilities.

The study recognises a trend of over emphasis within academic work on BIM and its associated tools; which can potentially hinder the application of other platforms or much simpler solutions. The research focus should shift to smaller organisations with low profit margins and spending power as the greater proportion of the construction sector. Or, how disproportionate is the construction industry in its use of modern tools and technologies. These are some of the critical questions in the path towards construction industry 4.0 revolution.

**Author Contributions:** M.B.J. and F.S. contributed equally to this study. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Institutional Review Board Statement:** Ethical review were not applicable to this study as publicly available information was used for the case studies.

**Informed Consent Statement:** Informed consent was obtained from all subjects involved in the study.

**Data Availability Statement:** All data is contained within the article.

**Conflicts of Interest:** The authors declare no conflict of interest.

## References

1. Ayinla, K.; Adamu, Z. Bridging the digital divide gap in BIM technology adoption. *Eng. Constr. Arch. Manag.* **2018**, *25*, 1398–1416. [CrossRef]
2. Santos, R.; Costa, A.A.; Grilo, A. Bibliometric analysis and review of Building Information Modelling literature published between 2005 and 2015. *Autom. Constr.* **2017**, *80*, 118–1363. [CrossRef]
3. Wang, L.; Huang, M.; Zhang, X.; Jin, R.; Yang, T. Review of BIM Adoption in the Higher Education of AEC Disciplines. *J. Civ. Eng. Educ.* **2020**, *146*, 06020001. [CrossRef]
4. Dansoh, A.; Oteng, D.; Frimpong, S. Innovation development and adoption in small construction firms in Ghana. *Constr. Innov.* **2017**, *17*, 511–535. [CrossRef]
5. Jelodar, B.M.; Wilkinson, S.; Tookey, J. Construction project innovation; a system controlled by construction project dynamics. In Proceedings of the Construction, Building and Real Estate Research Conference (COBRA 2018), London, UK, 23–24 April 2018.
6. Pellicer, E.; Yepes, V.; Correa, C.L.; Alarcon, L.F. The dilemma of innovation in the construction company: A decade of lessons learned. In *Project Management and Engineering Research: AEIPRO 2016*; Ayuso Muñoz, J.L., Yagüe Blanco, J.L., Capuz-Rizo, S.F., Eds.; Springer International Publishing: Cham, Switzerland, 2017; pp. 21–33.
7. Walker, D.H.T. Reflecting on 10 years of focus on innovation, organisational learning and knowledge management literature in a construction project management context. *Constr. Innov.* **2016**, *16*, 114–126. [CrossRef]
8. Dave, B.; Kubler, S.; Främling, K.; Koskela, L. Opportunities for enhanced lean construction management using Internet of Things standards. *Autom. Constr.* **2016**, *61*, 86–97. [CrossRef]
9. Noor, B.A.; Yi, S. Review of BIM literature in construction industry and transportation: Meta-analysis. *Constr. Innov.* **2018**, *18*, 433–452. [CrossRef]
10. Hasan, A.; Baroudi, B.; Elmualim, A.; Rameezdeen, R. Factors affecting construction productivity: A 30 year systematic review. *Eng. Constr. Arch. Manag.* **2018**, *25*, 916–937. [CrossRef]
11. Pan, Y.; Zhang, L. BIM log mining: Exploring design productivity characteristics. *Autom. Constr.* **2020**, *109*, 102997. [CrossRef]
12. Eliwa, H.; Jelodar, M.B.; Poshdar, M. Information technology and New Zealand construction industry: An empirical study towards strategic alignment of project and organization. In Proceedings of the 18th International Conference on Construction Applications of Virtual Reality (CONVR2018), Auckland, New Zealand, 21–23 November 2018.
13. Piccoli, G.; Pigni, F. *Information Systems for Managers: With Cases*, 4th ed.; Prospect Press: Burlington, VT, USA, 2019.
14. O'Hara, M.T.; Watson, R.T.; Kavan, C.B. Managing the three Levels of Change. *Inf. Syst. Manag.* **1999**, *16*, 63–70. [CrossRef]

15. Oti, A.; Kurul, E.; Cheung, F.K.T.; Tah, J. A framework for the utilization of Building Management System data in building information models for building design and operation. *Autom. Constr.* **2016**, *72*, 195–210. [CrossRef]
16. Schmidt, R.; Mohring, M.; Bar, F.; Zimmermann, A. The impact of digitization on information system design—An explorative case study of digitization in the insurance business. In *Business Information Systems Workshops*; Springer: Cham, Switzerland, 2017.
17. Piccoli, G.; Pigni, F. *Information Systems for Managers: Without Cases*, 4th ed.; Prospect Press: Burlington, VT, USA, 2018.
18. Zaher, M.; Greenwood, D.; Marzouk, M. Mobile augmented reality applications for construction projects. *Constr. Innov.* **2018**, *18*, 152–166. [CrossRef]
19. Rowlinson, S. Building information modelling, integrated project delivery and all that. *Constr. Innov.* **2017**, *17*, 45–49. [CrossRef]
20. Oraee, M.; Hosseini, M.R.; Papadonikolaki, E.; Palliyaguru, R.; Arashpour, M. Collaboration in BIM-based construction networks: A bibliometric-qualitative literature review. *Int. J. Proj. Manag.* **2017**, *35*, 1288–1301. [CrossRef]
21. Bortolini, R.; Formoso, C.T.; Viana, D.D. Site logistics planning and control for engineer-to-order prefabricated building systems using BIM 4D modeling. *Autom. Constr.* **2019**, *98*, 248–264. [CrossRef]
22. Xu, G.; Li, M.; Chen, C.-H.; Wei, Y. Cloud asset-enabled integrated IoT platform for lean prefabricated construction. *Autom. Constr.* **2018**, *93*, 123–134. [CrossRef]
23. Peansupap, V.; Walker, D.H. Information communication technology (ICT) implementation constraints. *Eng. Constr. Arch. Manag.* **2006**, *13*, 364–379. [CrossRef]
24. Ahuja, V.; Yang, J.; Shankar, R. IT—Enhanced communication protocols for building project management. *Eng. Constr. Arch. Manag.* **2010**, *17*, 159–179. [CrossRef]
25. Hasan, A.; Ahn, S.; Rameezdeen, R.; Baroudi, B. Investigation into post-adoption usage of mobile ICTs in Australian construction projects. *Eng. Constr. Arch. Manag.* **2019**, *28*, 351–371. [CrossRef]
26. Meng, Q.; Zhang, Y.; Li, Z.; Shi, W.; Wang, J.; Sun, Y.; Xu, L.; Wang, X. A review of integrated applications of BIM and related technologies in whole building life cycle. *Eng. Constr. Arch. Manag.* **2020**, *27*, 1647–1677. [CrossRef]
27. Zhong, D.; Li, X.; Cui, B.; Wu, B.; Liu, Y. Technology and application of real-time compaction quality monitoring for earth-rockfill dam construction in deep narrow valley. *Autom. Constr.* **2018**, *90*, 23–38. [CrossRef]
28. Wang, J.; Sun, W.; Shou, W.; Wang, X.; Wu, C.; Chong, H.-Y.; Liu, Y.; Sun, C. Integrating BIM and LiDAR for Real-Time Construction Quality Control. *J. Intell. Robot. Syst.* **2015**, *79*, 417–432. [CrossRef]
29. Yin, R.K. *Case Study Research and Applications: Design and Methods*, 6th ed.; SAGE Publications, Inc.: Los Angeles, CA, USA, 2018.
30. Jelodar, M.B.; Yiu, T.W.; Wilkinson, S. A conceptualisation of relationship quality in construction procurement. *Int. J. Proj. Manag.* **2016**, *34*, 997–1011. [CrossRef]
31. Jelodar, M.B.; Yiu, T.W.; Wilkinson, S. Dispute manifestation and relationship quality in practice. *J. Leg. Aff. Disput. Resolut. Eng. Constr.* **2016**, *8*. [CrossRef]
32. Shelton, J.; Martek, I.; Chen, C. Implementation of innovative technologies in small-scale construction firms. *Eng. Constr. Arch. Manag.* **2016**, *23*, 177–191. [CrossRef]
33. Cooper, H.M. *The Integrative Research Review: A Systematic Approach*; SAGE Publications, Inc.: Los Angeles, CA, USA, 1984.
34. Mignone, G.; Hosseini, M.R.; Chileshe, N.; Arashpour, M. Enhancing collaboration in BIM-based construction networks through organisational discontinuity theory: A case study of the new Royal Adelaide Hospital. *Arch. Eng. Des. Manag.* **2016**, *12*, 333–352. [CrossRef]
35. Flick, U. *An Introduction to Qualitative Research*, 3rd ed.; SAGE Publications: London, UK, 2006.
36. Gubrium, F.J.; Holstein, J.A. *Handbook of Interview Research: Context and Method*; SAGE Publications: Thousand Oaks, CA, USA, 2002.
37. Chen, P.; Partington, D. An interpretive comparison of Chinese and Western conceptions of relationships in construction project management work. *Int. J. Proj. Manag.* **2004**, *22*, 397–406. [CrossRef]
38. Glaser, B.G.; Strauss, A.L. *The Discovery of Grounded Theory: Strategies for Qualitative Research*; Aldine Transaction: Piscataway, NJ, USA, 2009.
39. Moore, D.R.; Dainty, A.R.J. Intra-team boundaries as inhibitors of performance improvement in UK design and build projects: A call for change. *Constr. Manag. Econ.* **2001**, *19*, 559–562. [CrossRef]
40. Hosseini, M.R.; Chileshe, N.; Zuo, J.; Baroudi, B. Adopting global virtual engineering teams in AEC Projects. *Constr. Innov.* **2015**, *15*, 151–179. [CrossRef]
41. Mehrbod, S.; Staub-French, S.; Mahyar, N.; Tory, M. Characterizing interactions with BIM tools and artifacts in building design coordination meetings. *Autom. Constr.* **2019**, *98*, 195–213. [CrossRef]
42. Ma, Z.; Cai, S.; Mao, N.; Yang, Q.; Feng, J.; Wang, P. Construction quality management based on a collaborative system using BIM and indoor positioning. *Autom. Constr.* **2018**, *92*, 35–45. [CrossRef]
43. Sutrisna, M.; Kumaraswamy, M.M. Advanced ICT and smart systems for innovative "engineering, construction and architectural management". *Eng. Constr. Arch. Manag.* **2015**, *22*. [CrossRef]
44. Darko, A.; Chan, A.P.; Adabre, M.A.; Edwards, D.J.; Hosseini, M.R.; Ameyaw, E.E. Artificial intelligence in the AEC industry: Scientometric analysis and visualization of research activities. *Autom. Constr.* **2020**, *112*, 103081. [CrossRef]
45. Sutrisna, M.; Goulding, J. Managing information flow and design processes to reduce design risks in offsite construction projects. *Eng. Constr. Arch. Manag.* **2019**, *26*, 267–284. [CrossRef]
46. Ma, X.; Chan, A.P.; Wu, H.; Xiong, F.; Dong, N. Achieving leanness with BIM-based integrated data management in a built environment project. *Constr. Innov.* **2018**, *18*, 469–487. [CrossRef]

47. Zhang, S.; Pan, F.; Wang, C.; Sun, Y.; Wang, H. BIM-based collaboration platform for the management of EPC projects in hydropower engineering. *J. Constr. Eng. Manag.* **2017**, *143*, 04017087. [CrossRef]
48. Ahn, S.; Han, S.; Al-Hussein, M. 2D drawing visualization framework for applying projection-based augmented reality in a panelized construction manufacturing facility: Proof of concept. *J. Comput. Civ. Eng.* **2019**, *33*, 04019032. [CrossRef]
49. Oh, M.; Lee, J.; Hong, S.W.; Jeong, Y. Integrated system for BIM-based collaborative design. *Autom. Constr.* **2015**, *58*, 196–206. [CrossRef]
50. Gondia, A.; Siam, A.; El-Dakhakhni, W.; Nassar, A.H. Machine learning algorithms for construction projects delay risk prediction. *J. Constr. Eng. Manag.* **2020**, *146*, 04019085. [CrossRef]
51. Beca. BIM in NZ Case Study Mason Bros. Commercial Precinct. BIM in NZ 2016. Available online: https://www.biminnz.co.nz/casestudies/2018/mason-bros-commercial-precinct (accessed on 1 July 2018).