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Integration and Interoperability for the Optimisation of Information Flow in Construction Project Lifecycle

[1]FH Abanda, [2]Marcelline Blanche Manjia, [3]Ursula Joyce Merveilles Nana Pettang, [4]Chrispin Pettang

[1]Oxford Institute for Sustainable Development
School of the Built Environment
Faculty of Technology, Design & Environment
Oxford Brookes University, Oxford, UK

[2,3,4] Department of Civil Engineering
National Advanced School of Engineering
The University of Yaoundé I, Yaoundé, Cameroon

Abstract

Integration and interoperability are paradigms that have been proposed to alleviate challenges associated with data exchange between systems for managing construction project information. However, with the overwhelming number of emerging software in practice, their performance vis-à-vis integration and interoperability especially from a lifecycle perspective is yet to be fully explored. This study investigates the use of emerging ICT in the optimisation of information exchange across the lifecycle of a construction project. A quantitative approach was used to achieve the aim of this study. The first main finding of this study is that BIM is the most integrated and most effective technology when compared with other technologies. The second most important finding is the fact that most professionals will consider exchanging data at the developed design-technical design and technical design-construction phases.

Key words: BIM, Construction Project Lifecycle, Integration, Interoperability, Information Flow

1. Introduction

The construction industry is a data/information intensive domain. For example, Egan (1998) stated that a typical house contains 40 000 parts compared to an average car which has 3 000 parts [1].
. This is further exacerbated by the fact that each component has properties that characterises it. Paradoxically, it is the least, only better than the agricultural and hunting sector in digitising its practices (Agarwal et al., 2016) that can lead to improved efficiency. Harnessing this number of components and their properties can provide opportunities to transform its related data into knowledge for informed decision-making about the delivery of construction projects [2].. This is particularly important if this is thought of in a life cycle sense and how machines or software play a role in processing and transforming input-output data into actions aimed at improving the performance of built-assets. There is an overwhelming amount of research that shows the application of digital technologies can lead to the change value creation paths in organisations (Wessel et al. 2021) [3]... Current research focuses on digital transformation effects or changes on organisations with no detail on types of processes that may cause the change[3]. At the project data/information exchange in construction practice typically still takes place manually, with individuals or organisations reformatting and manually distributing information (Dawood et al., 2002) [4].. and in document (Anumba et al. 2008) [5]... This manual approach often leads to data losses and inefficiencies through rework which often culmininate in time and cost overruns [5]... In the past, for each process or task a separate systems (island system) provided many benefits, but resulted in some problems such as an inability to connect systems (Zafary, 2020) [6]. The

*Corresponding author: Address: Faculty of Engineering, Department of Civil Engineering Sakarya University, 54187, Sakarya TURKEY. E-mail address: caglar@sakarya.edu.tr, Phone: +902642955752

aforementioned weaknesses often lead to waste in construction ([5].., Abukhder and Munns 2005[7]..). The advent of BIM raised hope of overcoming data /information exchange challenges (Demian and Walters, 2013) [8].. ; although significant progress has been made, there is more to be done to ensure seamless information exchange and flow between systems. Without addressing these issues it is hard to see how the much desired changes of digital transformation can be achieved especially at the projet level. This is further exacerbated by the avalanche of various software and hardware systems common in our markets. This raises so many questions, what are the different software ? How do they communicate with each other? In which construction phase are the software used in ? Which file formats do the different software import/export ? What plugins do the software support ? This study seek to answer the aforementioned questions.

2 Overview of Related Concepts

2.1 ICT Technologies

In this section, the definitions of the relevant concepts will be provided which will aid in facilitating understanding amongst readers. Firstly, high-level concepts (ICT, Industry 4 and Construction 4) that underpin digital technologies will be examined. This will provide the basis to further define ICT technologies in the second instance.

There is no universal consensus as to what really is ICT (Zuppo, 2012) [9]. . Various authors have defined it differently (Adwan and Al-Soufi 2016[10].; Ying and Lee 2016[11]. ; Ibem and Laryea 2014) [12].. . Despite this lack of consensus, a common aspect of the various perspectives is that ICT are technologies that enable the production, storage and handling of information, and facilitate different forms of communication between human beings and electronic systems and amongst electronic systems in digital, binary computer language. Christensson (2010) further argues that ICTs provide access to information through telecommunications [13]. It is similar to Information Technology (IT), defined as anything related to computing technology, such as networking, hardware, software, the Internet, or the people that work with these technologies [13]., but focuses primarily on communication technologies. This ambiguity and lack of consensus in the definitions of ICT is further compounded by the fact in the construction sector it is often considered synonymous with information technology and construction (ITC) [10]. and digital technologies (Ibem and Laryea, 2014) [13].

Industry 4.0/Construction 4.0: The need to computerise knowledge has been growing over the years. In the 90s, in Japan, a Japanese professor coined the term 'digital economy' to mean an economy that is based on digital technologies (Tapscott, 1997) [14]. At the time this was largely interpreted to mean conducting business through markets based on the internet and the World Wide Web. Thus, the term has been synonymously called the Internet Economy, New Economy, or Web Economy. Similar to the 'digital economy' concept, the term 'Industrie 4.0' emerged in 2011 as a future project within the framework of the German high-tech strategy (BDF, 2018) [15]. Since then, the concept, also known as 'Industry 4.0' in English with shortened acronyms of I4.0 or simply I4, has been gaining interest amongst research centres, universities, and companies. Despite this popularity, its definition is still very amorphous with a lack of consensus as to its exact meaning (Hermann et al., 2015) [16]. Even key promoters of the idea, the 'Industrie 4.0 Working Group' and the 'Plattform Industrie 4.0', only describe the vision, the basic technologies the idea aims at, and selected scenarios but do not provide a clear definition. However, it is generally understood to mean the 4th Industrial Revolution with the goal of digitising the industry. The ultimate goal of this revolution is to take the automation of manufacturing processes to a new level by introducing customized and flexible mass production technologies (Martin, 2017) [17]. Effective automation can be achieved when machines operate independently or cooperate with humans in creating a customer-oriented production field that constantly works on maintaining itself [17]. The machine rather becomes an independent entity that is able to collect data, analyze it, and advise upon it. The idea behind Industry 4.0 is to create a social network where machines can communicate with each other, called the Internet of Things (IoT) and with people, called the Internet of People (IoP). As vague as the Industry 4.0 concept, its components are still very unclear. However, Hermann et al. (2015) listed Cyber-Physical Systems, IoT, Smart Factory, Internet of Services, Smart Product, Machine-to-Machine and Cloud as components of Industry 4.0 although Cyber-Physical Systems, IoT, Smart Factory, and Internet of Services are often listed in academic literature [17].). What does Industry 4.0 mean to the construction industry? A similar concept, Construction 4.0 has been used by the European Construction Industry Federation to mean the digitisation of the construction industry, with BIM central to it, although not the only element. Many other technologies such as advanced 3D Printing, drones, and robots are part of Construction 4.0. In fact, everything connected to ensure accurate real-time information processing, leading to smoother, error free, faster construction is part of Construction 4.0.

Distributed ledger technologies (DLT): Distributed ledgers are a type of database that is spread across multiple sites, countries or institutions, and is typically public (GOS, 2016) [18].

Unmanned Vehicle Systems: These are vehicles capable of sustained operation without the need of a human operator on board. In construction, these vehicles can be classified into Unmanned Aircraft Systems (UAS), Unmanned Ground Vehicles (UGVs), Unmanned Aerial Vehicles (UAVs), and Unmanned Underwater Vehicles (UUVs). The Unmanned Aircraft Systems (UAS) are at times called Unmanned Aerial Vehicles, drones or flying robots.

3D-Printers: The concept of 3D printing will be explained using Additive Building Manufacturing (ABM). The term "Additive Manufacturing" (AM) refers to the set of additive manufacturing production processes starting from digital models, as opposed to traditional subtractive techniques (machining by chip removal, cutting and drilling) (Conner et al., 2014) [19]. Additive Building Manufacturing (ABM) involved the use of large robots on a building site to 3D Print (extrude) building materials to construct buildings (AABM, 2016) [20]. Aerial ABM refers to aerial robotic construction systems that enable aerial robots to 3D print building structures autonomously [20].

Building Information Modelling (BIM): The UK Construction Industry Council defines BIM as … "an innovative and collaborative way of working that is underpinned by digital technologies which support more efficient methods of designing, creating and maintaining the built environment".

City Information Modelling (CIM): City Information Modeling generally involves building a 3D city model that connects with BIM and other contextual data source or analysis tool of various city components, including buildings, roads and public spaces (open data), streetlights (sensors/IoT), and even people on the street (social media) (Hisham, 2018) [21].

Geographical Information Systems (GIS): GIS can be defined as a computerized system for capture, storage, retrieval, analysis and display of spatial data describing the land attributes and environmental features for a given geographic region, by using modem information technology (Thurgood and Bethel, 2003) [22].

The Automatic identification and data capture (AIDC) (aka Automatic Identification," "Auto-ID," and "Automatic Data Capture"): AIDC refers to a sequence of data capture prior to identification (Furness, 2000) [23]. The aspect of identification may refer to the identification of animate or inanimate objects, data, locations and events. The data aspect can be of a simple data string that allows reference or linking to data or information stored elsewhere (so called ``licence plate" concept), or a portable data file, each with attributes that extend beyond the process of identification.

Configurator: A configuration system can be defined as an IT-system capable of ''combining well-defined building blocks governed by rules and constraints into a product'' (Andreasen, 1987) [24]. The implementation of a configuration system thus implies a well-defined modular structure of the product. The basis for a product configuration system is a product model containing ''all relevant information concerning a given product during the lifecycle'' (Krause et al., 1993) [25].. Product configuration as described by Hvam et al. (2008) [26]. is an effective way of structuring products composed of standard parts, and product configuration is also a method of presenting products to customers. An example of a configurator is Configurator 360 developed by Autodesk.

Internet of Things: A conceptual framework that leverages on the availability of heterogeneous devices and interconnection solutions, as well as augmented physical objects providing a shared information base on global scale, to support the design of applications involving at the same virtual level both people and representation of objects (Atzori et al., 2017) [27].

Virtual Reality (VR): Virtual reality (VR) is a technology which allows a user to interact with a computer-simulated environment, whether that environment is a simulation of the real world or an imaginary world (Mandal, 2013)) [28].

Augmented Reality (AR): AR is a technology that supplements the real world with virtual (computer generated) objects/elements and enables users to interact with the virtual elements (Bekele and Champion, 2019) [29].

Mixed Reality (MR): Mixed Reality (MxR) blends elements from both the real and virtual environments to create a real-virtual environment that enhances our perception of both environments [29]. This environment enables interaction between users, virtual elements, and the real world, leading to a user-reality-virtuality interaction and relationship space. Unlike AR, where the real environment is dominant, MxR does not allow one environment to dominate the other, instead both environments benefit from each other's elements.

2.2 System Integration & Interoperability and Related Studies

Having reviewed the various common technologies used in construction, it is imperative to examine two main concepts that allow for information exchange or sharing between them. These are integration and interoperability.

Managing information during the lifecycle of a construction project is becoming more and more important in contemporary construction project management with an increasing amount of information being produced by AEC. This information comprises of building geometry, spatial relationships, and quantities and properties of building components. Efficient processing of these kinds of information to support different AEC professionals is essential for a successful project management. Efficient processing of information depends largely on how the computer programmes interface (i.e. integration) and/or how easy such information can easily be exchanged between two or more computer systems (i.e. interoperability).
To enhance understanding, the terms “component” and “system”, relevant to these two concepts will have to be explained. According to IEEE 610 components are one of the parts that make up a system, while a system is a collection of components organised to accomplish a specific function or a set of functions.

The term integration refers to the process of combining components into an overall system (after IEEE 610). From an information management perspective, it refers to the process of combining information or data from same or different sources. Five different BIM integration examples have been examined in Wastiels and Decuypere (2019) [30]. The first is about how different building components (with their quantities) are manually linked to predefined LCA profiles available in the LCA software database or creates new LCA profiles where needed. The second method is about how BIM data is imported data (in IFC format) and linked to predefined LCA profiles available in the LCA software databases. Thirdly, the BIM Viewer is used ion linking LCA profiles. Fourthly, and LCA plugin is used to link LCA profiles to BIM objects within the native BIM environment. Lastly, LCA information is included in the BIM objects that are used in the BIM model.

According to IEEE 610, interoperability is the ability of two or more systems (or components) to exchange and subsequently use their information. Consequently, interoperability is concerned with the ability of systems to communicate – and it requires that the communicated information can be understood by the receiving system - but it is not concerned with whether the communicating systems do anything sensible as a whole. The interoperability between two systems could be fine, but whether the two systems as a whole actually performed any useful function would be irrelevant as far as the interoperability is concerned. The importance of system integration and interoperability has led to a surge in research in the same of late. Chen et al (2015) [31]. focused on the integration of BIM related technologies such as RFID, 3D laser scanning, cameras, GIS, and GPS. The authors went on to state that “there is a general lack of studies on interoperability of data among different BIM software programs and hard data-acquisition technologies” [31]. Most recent papers concerned with BIM technology integration focus on specific issues such as sustainability (Olawumi et al., [32] or more mainstream topics such as GIS (Hijazi et al., 2018) [33]., or sensor technology (Liu et al., 2018) [34]. Also, emphases have been placed on new technologies such as AR/VR (Gan et al., 2022) [35], robotics (Zhang et al., 2022)[36]. and the IoT (Sarkar et al., 2022)[37] and how they can be successfully integrated with BIM to improve the management of construction information in the industry. Taking the virtual spectrum further, integrating robotics into BIM "could represent the next step towards the correct design and application of automated construction processes in the AEC" (Meschini et al., 2016) [38]. Despite recent increase in research about BIM integration with other technologies, the emerging nature and multiplicity of ICT means further research is still needed. The main questions: How does BIM interfaced with other ICTs (e.g. robots, 3D laser scanners, 3D printers, etc)? Do professionals reflect on the format of their output data during the processing of the same? Do professionals consider other phases in the project lifecycle during the processing of their data?

3. Research Methods

A systematic approach consisting of using project lifecycles as a lens through which to identify the different technologies and their applications was adopted. Given that most authors hardly provide a clear distinction about the boundaries of the different phases of projects, the Royal Institute of British Architects (RIBA) plan of work was used whereby the different technologies were mapped against each of the phases (see Figure 1).

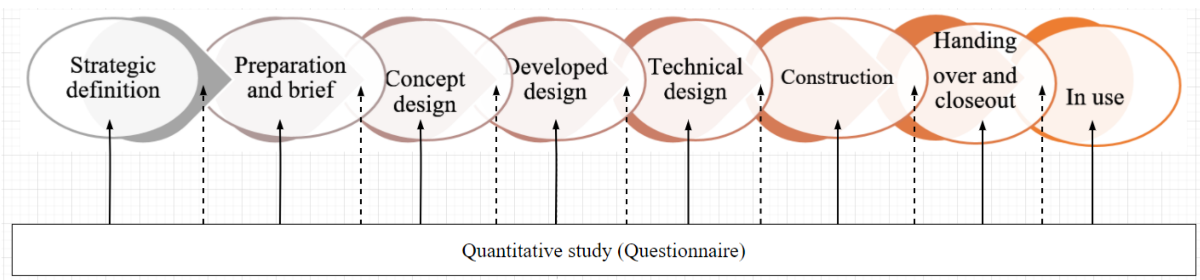


Figure 1. Construction life cycle phases

The proposed approach presented in Figure 1 facilitates the identification and alignment of the different ICT and their applications with the different phases of a construction project lifecycle. The continuous arrows indicate areas or phases where ICTs are relevant or can be applied. The chain lines indicate boundaries involving two different phases where ICTs can be integrated, are interoperable or where there is information exchange.

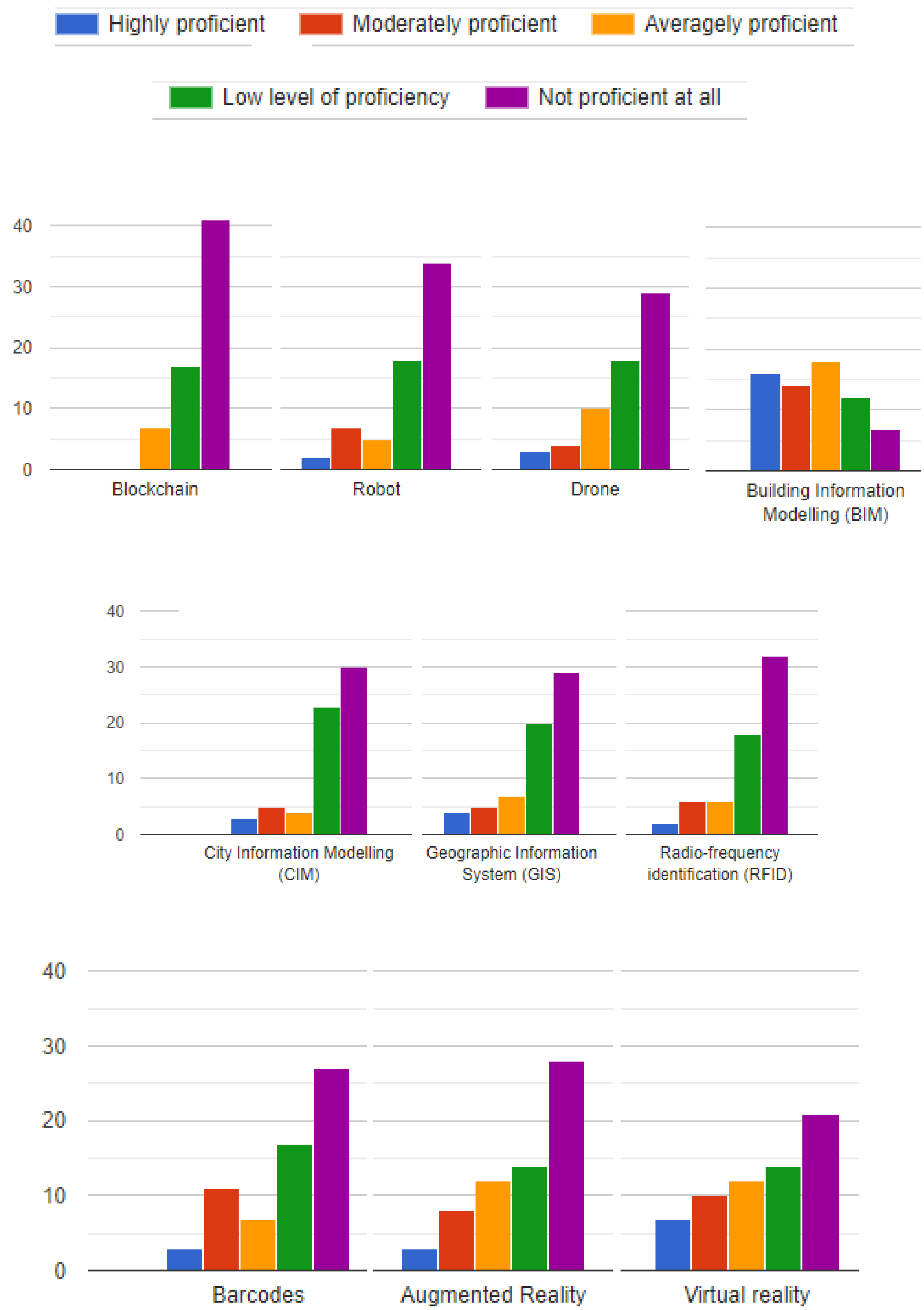
4 Results

4.1 Data Analysis

As discussed in section 3, the three phases used for analysis and classification of the different ICT and their applications are construction planning, construction, and operation & maintenance phases.

4.2 Response rate

In total, out of the 130 dispatched questions, 67 responses with complete answers were received. The survey was conducted between the period 1st March 2021 and 31st July 2021. The proficiency of the respondents have been presented in Figure 2. The level of proficiency of those that used the different technologies in construction is presented in Figure 2.


Highly proficient
Moderately proficient
Averagely proficient
Low level of proficiency
Not proficient at all
40
30
20
10
0
Blockchain
Robot
Drone
Building Information Modelling (BIM)
40
30
20
10
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City Information Modelling (CIM)
Geographic Information System (GIS)
Radio-frequency identification (RFID)
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Barcodes
Augmented Reality
Virtual reality

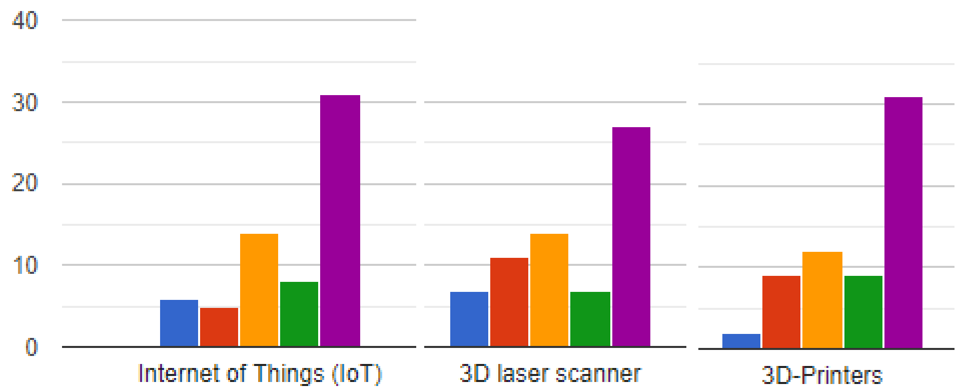
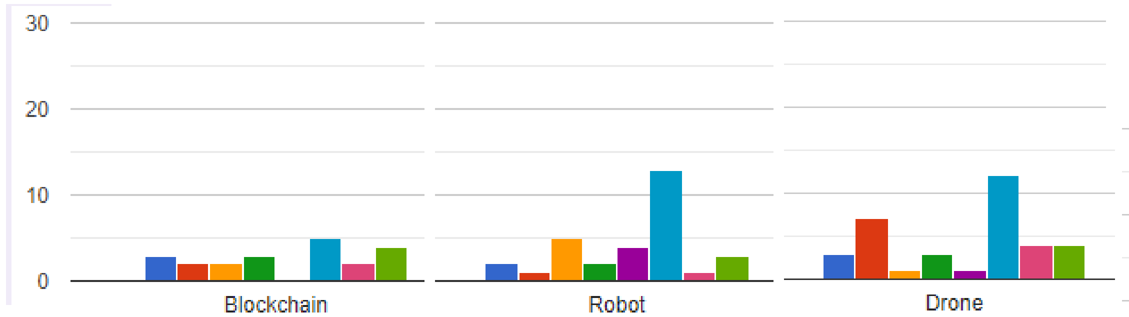


Figure 2: Experience of respondents

The charts in Figure 2 suggest most of the respondents were/are proficient in BIM, with 16 Highly proficient and 14 Moderately proficient. This is followed by 3D laser scanners with 7 and 11 respondents that confirmed they were Highly and Moderately proficient respectively. Blockchain was the category with the highest number of not experience professionals where 41 said they were "Not proficient at all". This in a way validates the data collected as, those providing have a reasonable level of experience in the use of the different technologies.

4.3 ICT versus Project delivery phases

The researchers sought to enquire in which of the project delivery phases they have applied each of the technologies. The result for the question is presented in Figure 3.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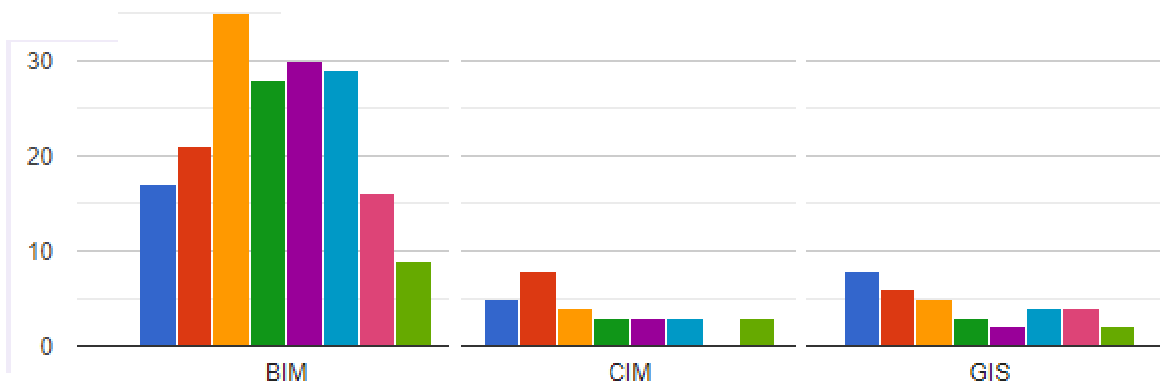
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CIM
GIS

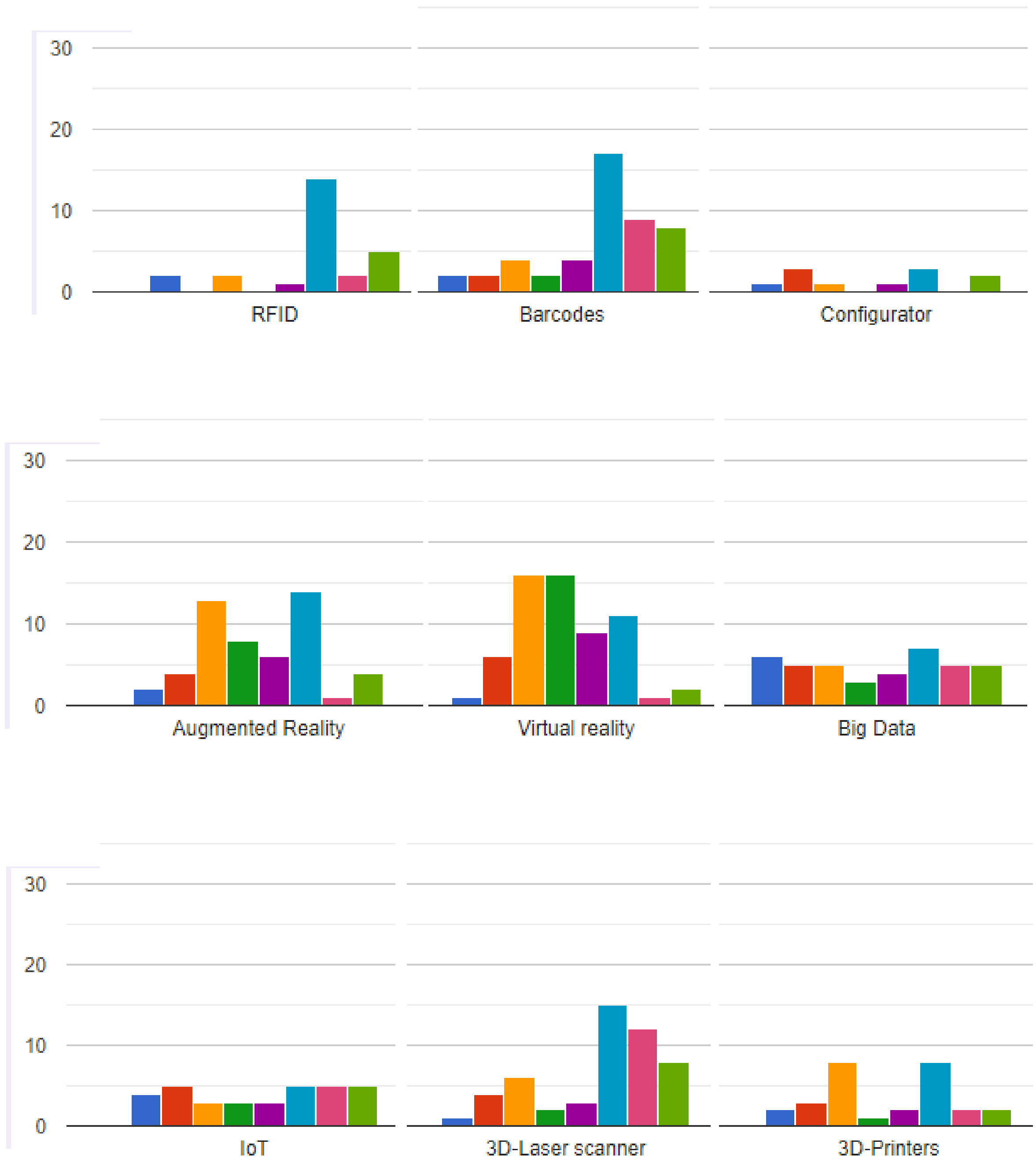


Figure 3: ICT applications and construction lifecycle

Based on Figure 3, it can be concluded that BIM has been applied to all the other phases more than any of the emerging ICT. Out of the 8 phases, BIM has been applied in 5 phases more than any of the technologies: Preparation and brief (21), Concept (35), Developed design (28), Technical design (30) and construction (29). The digits in brackets indicate the number of respondents who have applied BIM in the phase. Amongst these 5 categories, even though Preparation and brief with 21 respondents is the lowest, it is by far higher than any emerging ICT applied on other phases. On the other hand the configurator is the lowest to be used in the various construction phases. This is very surprising as BIM has been widely used in the different phases, yet not in facilitating configuration despite it being an enabler of the configuration principle (Farr et al., 2014) [39]..

4.4 Effective application of ICT in the various phases

The researchers sought to enquire how effective is any of the technologies when used in project delivery phases. The result is presented in Figure 4.

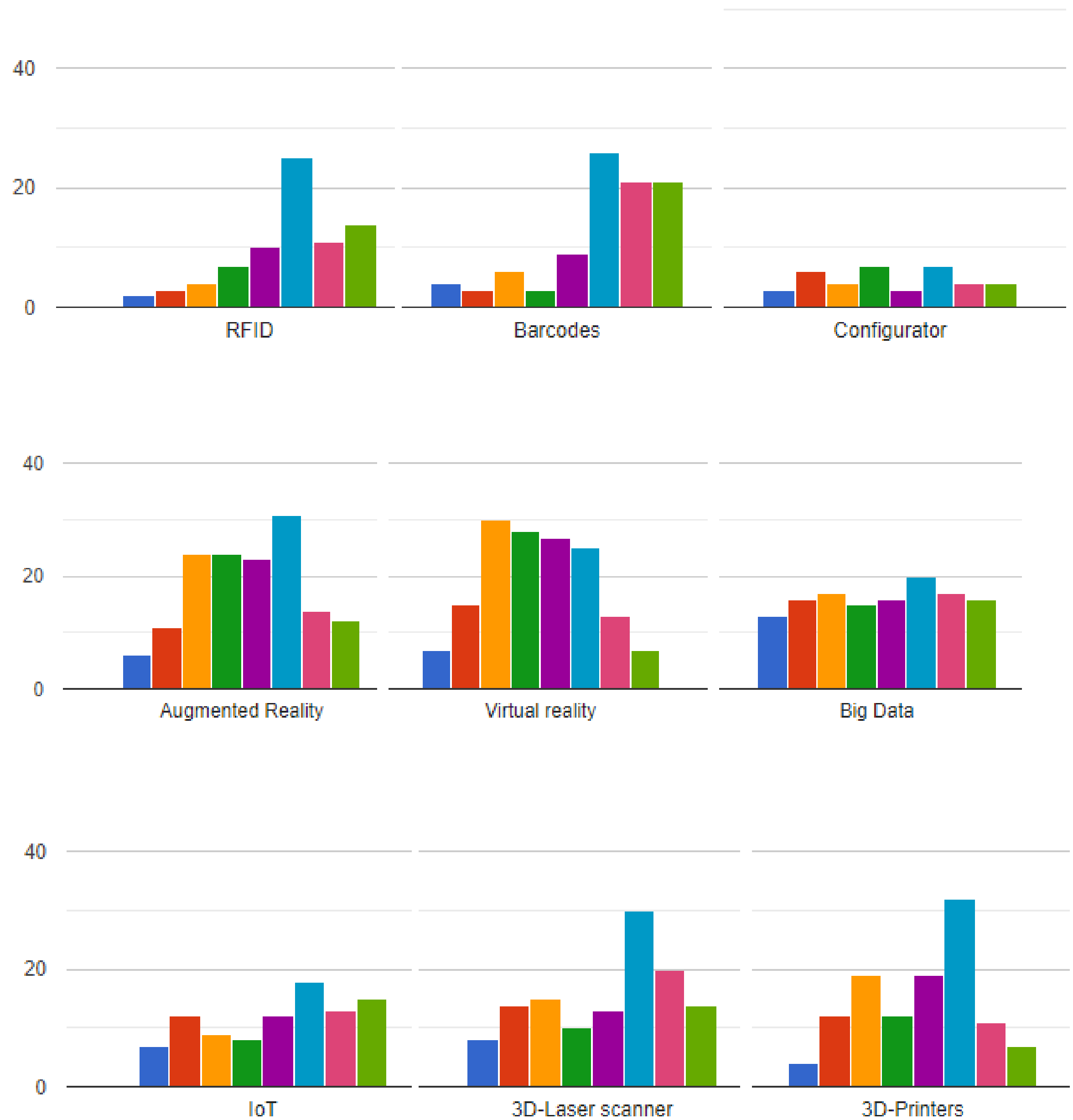
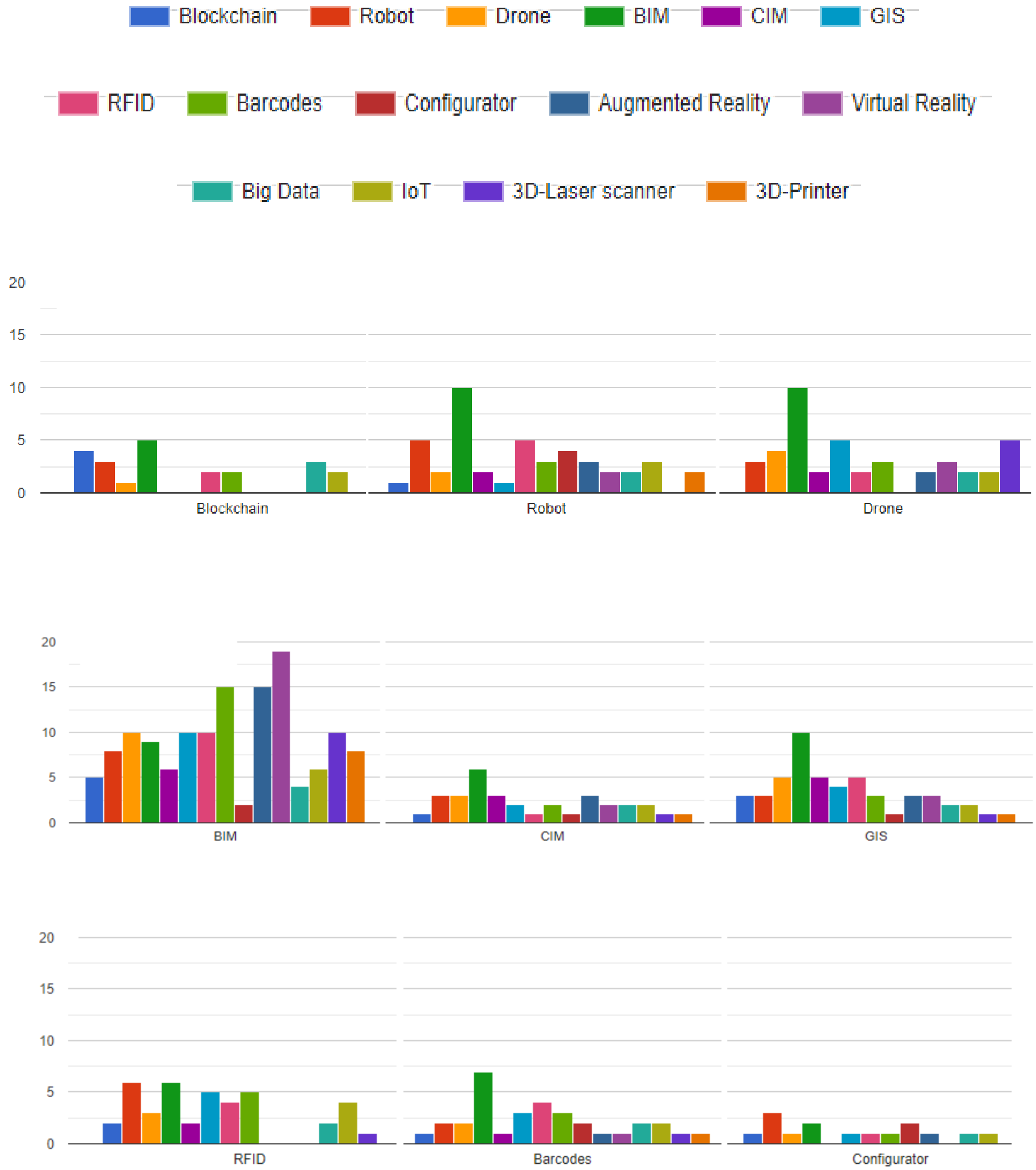


Figure 4: Effectiveness of ICT applications in the lifecycle phases

Figure 4 suggest that, BIM can be effectively applied in most of the phases than other technologies. In fact the top 5 areas where BIM can be effective are Preparation and brief (35), Concept (49), Developed design (48), Technical design (47) and construction (44). It is important to note that, other than BIM, the highest of all other technologies is Robot where 35 respondents confirmed its effectiveness when used in the construction phase.

4.5. Technology Integration for Efficiency of information exchange

The participants were asked about the technologies they have integrated in order to improve efficiency in information sharing. The responses have been captured in Figure 5.



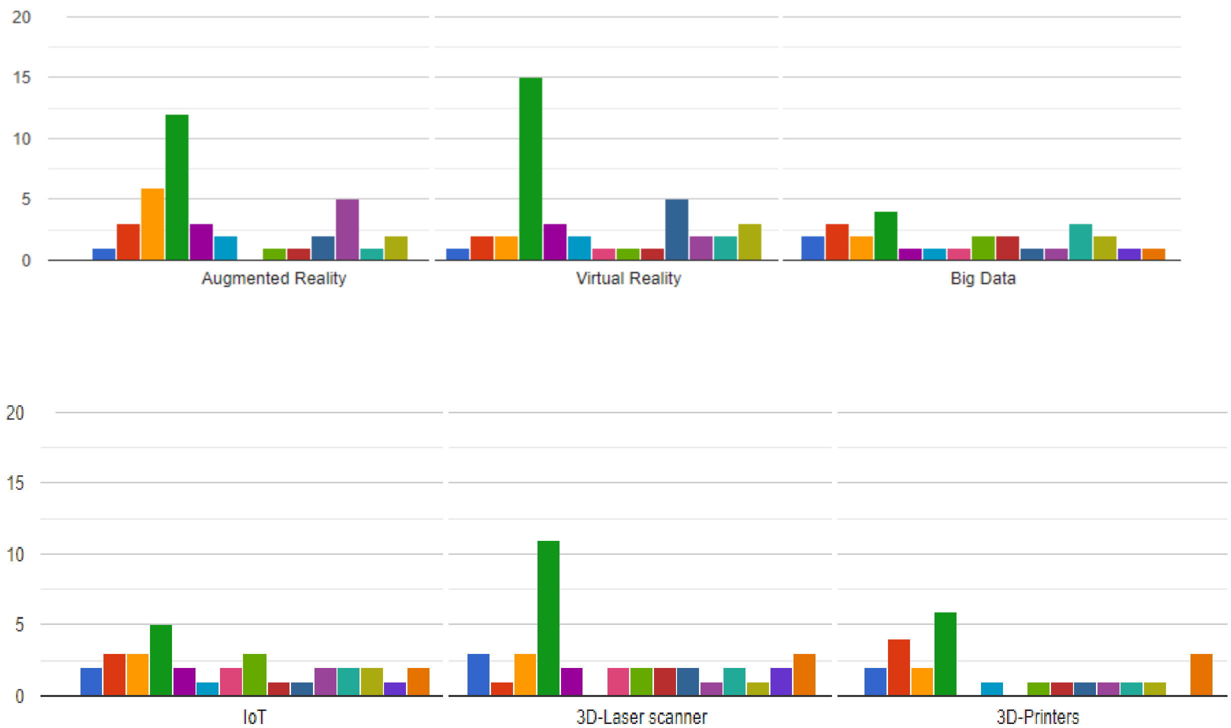
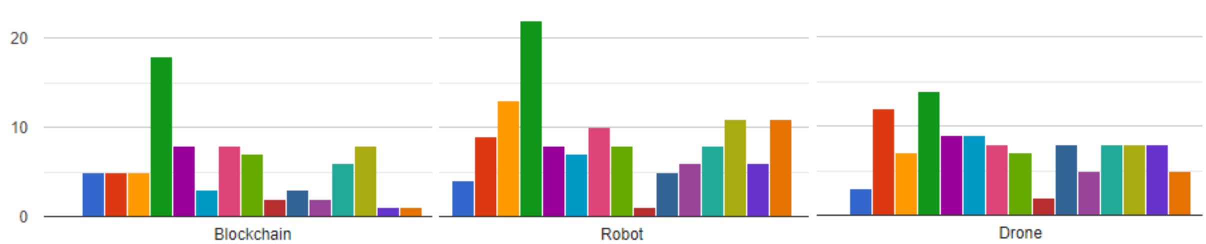


Figure 5: Technology integration

Based on Figure 5, BIM system is the highest to have been integrated with other technologies. On the other hand, 3D printers was the least category to have been integrated with other technologies.

4.6. Efficiency of technology integration

The participants were asked to give provide their views of the technologies that can be integrated in order to improve efficiency of their use. The result was presented in Figure 6.



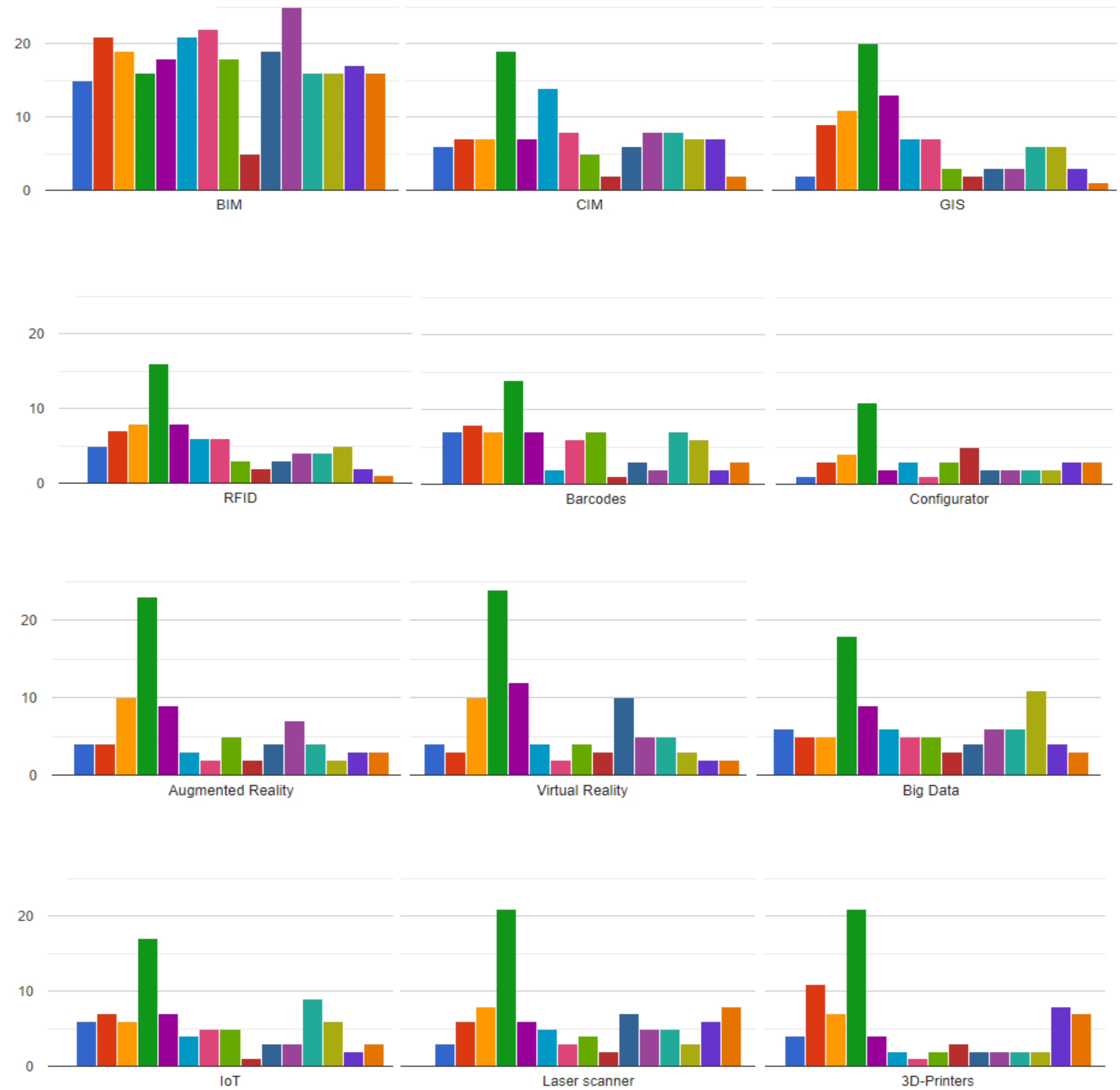
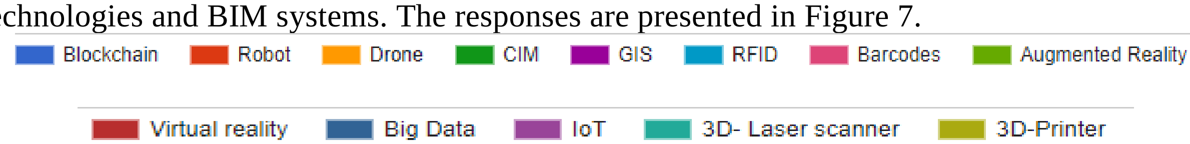


Figure 6: Efficiency of technology integration

Based on Figure 6, BIM is the technology that will lead to the highest efficiency when integrated with other technologies.

4.7. Frequency of exchange data/information between software systems

The researchers sought to establish the frequency of exchange of data/information between other technologies and BIM systems. The responses are presented in Figure 7.



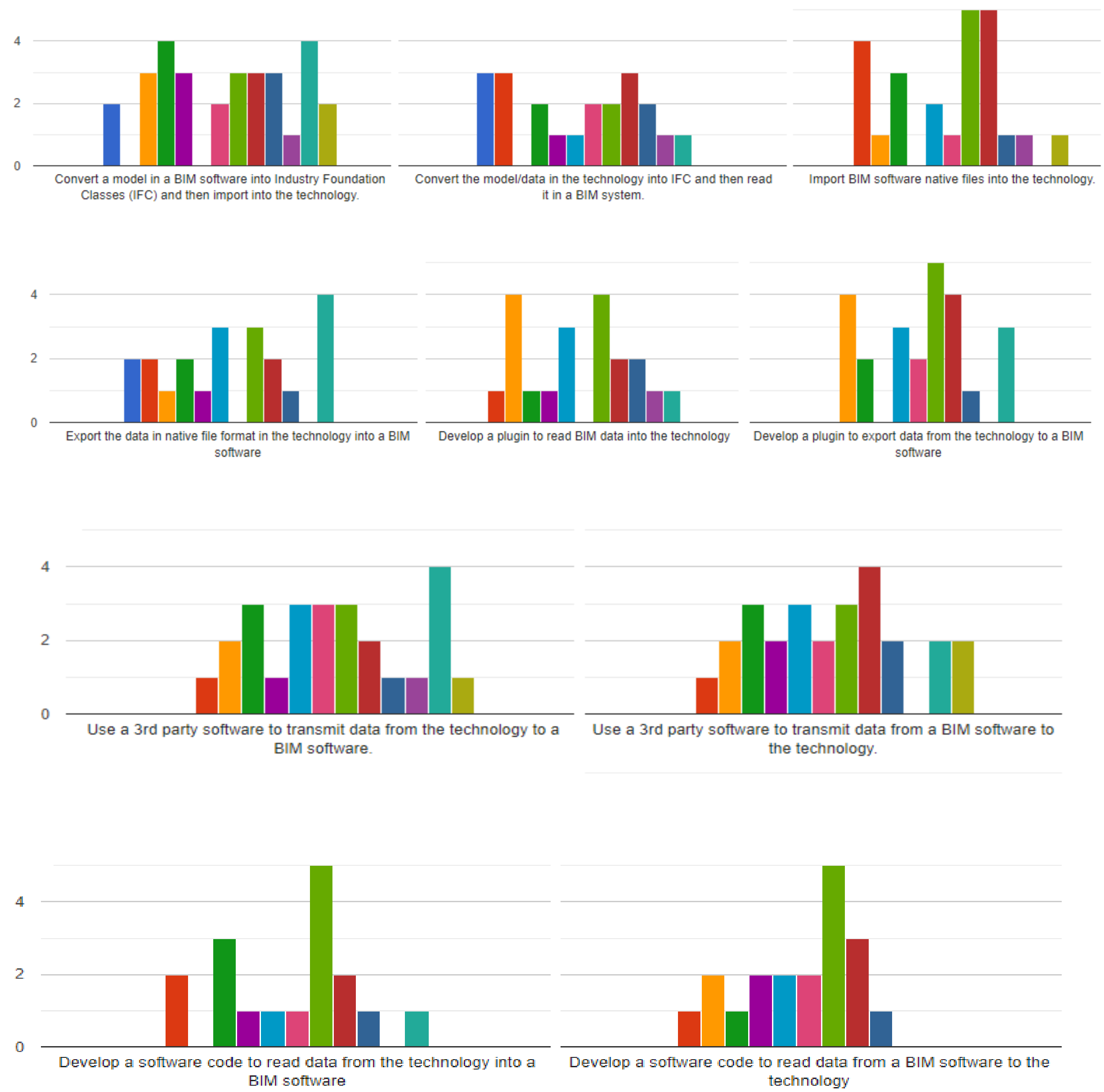
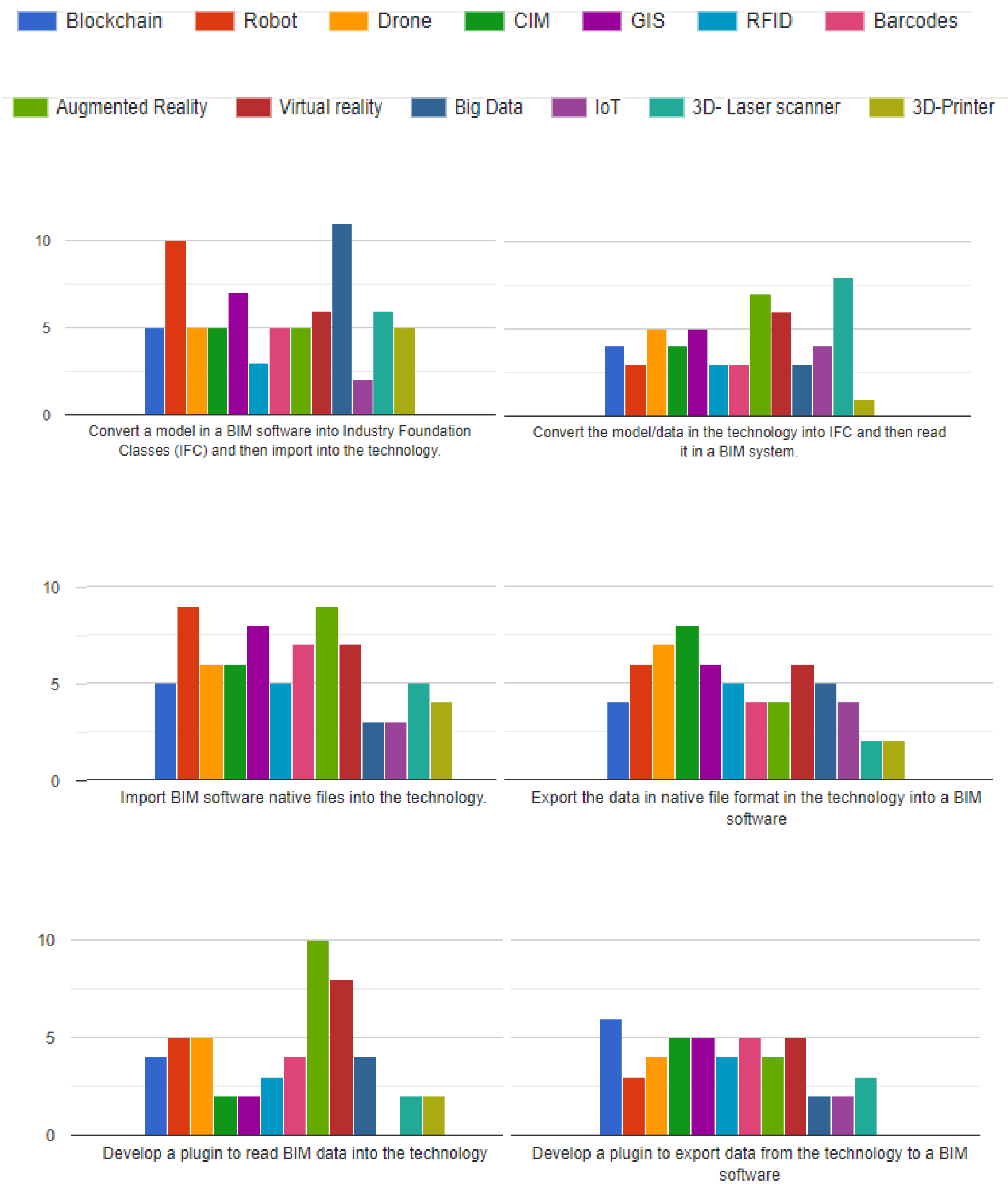


Figure 7: Frequency of exchange data/information between software systems

Figure 7 suggest that the most frequently used method for data/information exchange is by converting a model in a BIM software into Industry Foundation Classes (IFC) and then importing it into a given technology. Perhaps this is the case because of the fact that IFC has been recommended as an industry standard for exchanging BIM compliant project information.

4.8 Method of exchange data/information between software systems

The researchers sought to establish the best method for exchanging data/information between other technologies and BIM systems. The responses and presented in Figure 8.



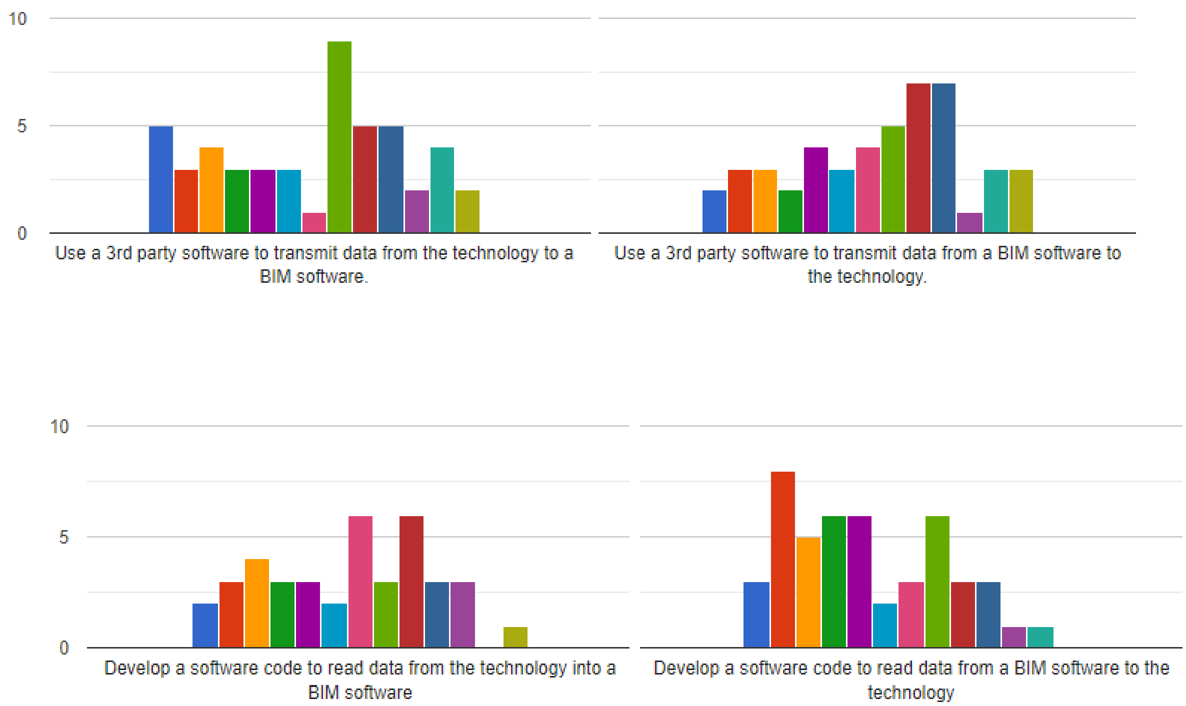


Figure 8: Best method of exchange data/information between software systems

The results in Figure 8 shows that the best method for exchanging information was through the conversion of a model in a BIM software into Industry Foundation Classes (IFC) and then import into a given software. The second-best method was to import BIM software native files into a given software.

4.9 Frequency of consideration data/information exchange between phases of construction lifecycle

The researcher sought to establish whether professionals do reflect or consider how their data will be passed to the other phases of the construction lifecycle when capturing data from the different ICTs. The responses are presented in the charts in Figure 9.

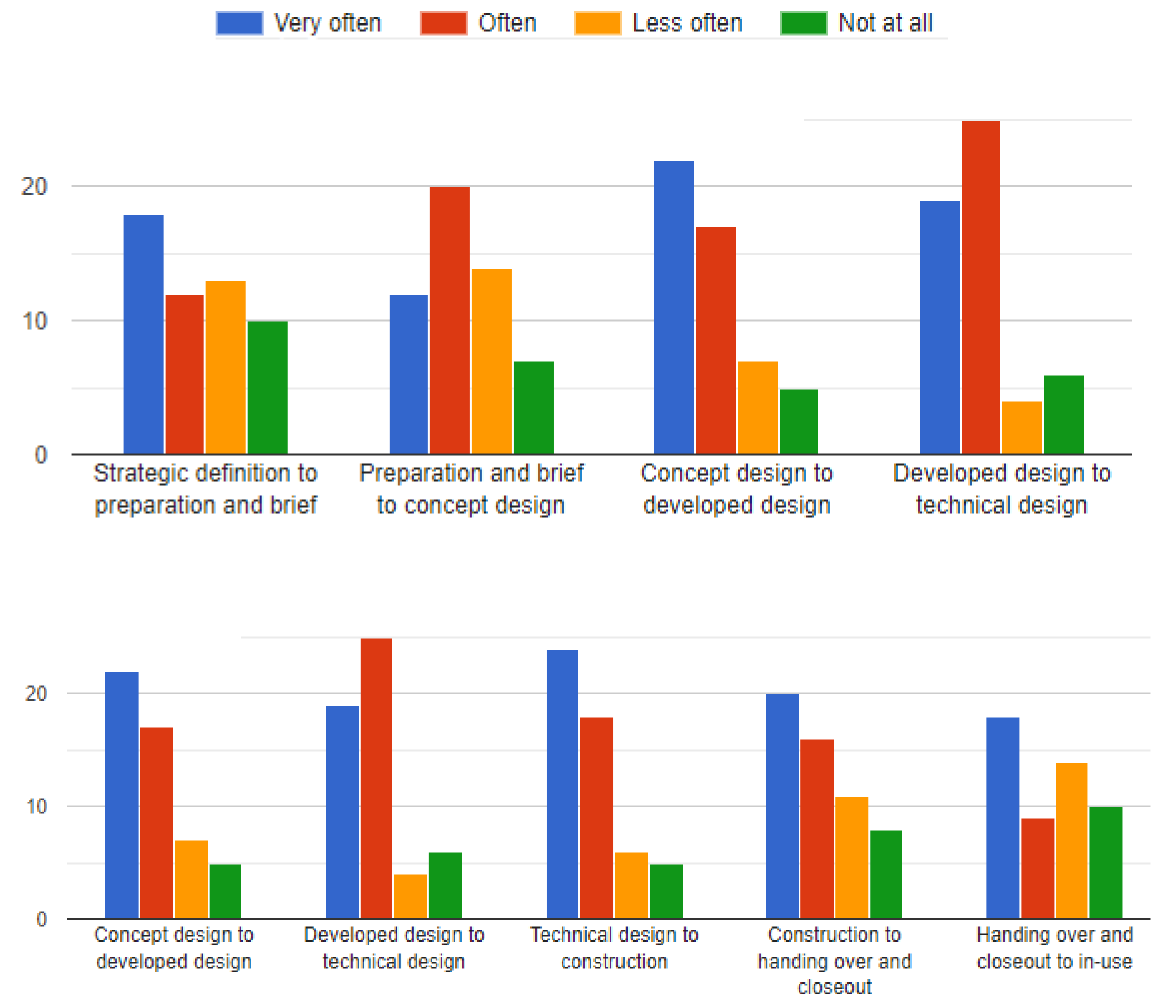


Figure 9 : Consideration data/information exchange between phases of construction lifecycle

Based on Figure 9 the Developed design to technical design and the Technical design to construction were the two phases where respondent say they will consider data/information exchange between the different phases in a project lifecycle.

5. Findings

The study yielded 5 main findings.
The study revealed that BIM was the most common technology used in all the construction phases than all the others. Specifically, BIM was applied in the concept phase than all the other phases. A study in Malaysia, revealed that of the 95 professionals that participated in a survey, 21.1%, 48.4% and 4.2% have used BIM in the Conceptualisation, Design and Execution phases respectively (Memon, 2014) [40].. The study revealed 26.3% have used BIM in all the phases. This study by Memon (2014) corroborates StK (2018) [41]., where it was argued that despite a rapidly growing

interest in using end to end BIM solutions on projects, some are still using in initial phases and some in advanced stages.
Secondly it emerged that, BIM is the most effective of all the technologies. Specifically, it is most effective in the concept, followed by the developed design and technical design phases.

Thirdly, it emerged that BIM is the technology that has been integrated with most of the technologies. Also, the study revealed 3D printers is the least to have been integrated with other technologies. Furthermore, the study revealed BIM yields the highest efficiency when integrated with other technologies. This has the potential of enhancing informed decision-taking (Shao et al. 2012) [42].. As argued by Zhou et al. (2018) [43]. integrating the different technologies can facilitate better decision-making based, on the proviso that information is complete.
Fourthly, the study revealed IFC is the most preferred and used method in converting and exchanging a model between BIM software systems.

Fifthly, the participants stated that they will consider exchanging data at the developed design-technical design and technical design-construction phases.

6. Conclusions

In this study a detailed examination of the various ICT has been examined. The definitions, applications of the various ICTs, their benefits and barriers to their adoption were presented. The study also revealed that although integration and interoperability of ICTs is an important strategy to maximise information exchange between systems and project stakeholders, research in this area is still in its infancy. Combining more than one technology in each phase of project lifecycle rather than tasks could guide practitioners towards effective application of ICTs. In fact in the recent Autodesk University Conference in London, it emerged that by integrating BIM, IoT and Artificial Intelligence, greater efficiency and productivity can be achieved in the construction industry. Thus, as a recommendation, it is important to focus future research on which ICTs can be combined together in order to achieve certain tasks at different phases of project lifecycle as in many cases more than one technology is used in an application.

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