School of Design and the Built Environment

Developing a Governance Framework to Assist with the Adoption of Sensing Technologies in Construction

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Declaration

To the best of my knowledge and belief this thesis contains no material previously published by any other person except where due acknowledgment has been made.

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university.

The research presented and reported in this thesis was conducted in accordance with the National Health and Medical Research Council National Statement on Ethical Conduct in Human Research (2007) – updated March 2014. The proposed research study received human research ethics approval from the Curtin University Human Research Ethics Committee (EC00262), Approval Number HRE2019-0052-07.

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Abstract

The construction industry lags behind other industries in the uptake of sensing technologies that have a great potential to provide the construction industry with safer, more productive and even higher quality processes. However, the fragmented and temporary nature of construction projects, along with many more barriers, challenge the adoption and implementation process of sensing technologies in this industry.

This research was aimed at discovering factors that dominate the adoption of sensing technologies in construction and ultimately developing a governance framework that can facilitate decision making processes and assist with the adoption of sensing technologies in the construction industry. To achieve this aim, the study was designed and conducted to, first, explore the current knowledge and status of sensing technologies in both construction management research and real construction projects. This step was meant to identify common types of sensing technologies applicable to the improvement of construction performance and investigate the extent to which the identified technologies have already been implemented in real construction projects. Second, the research would focus on construction stakeholders' perceptions of sensing technologies to discover what motivates them to employ such technologies and what deters them from adopting the technologies. The findings from this part of the research inform the development of the governance framework.

Guided by a literature review on the applicability of various types of sensing technologies, this research utilised quantitative methods of data collection and analysis to report on the current status of selected types of sensing technologies that have already been implemented in construction projects and the level of their pervasiveness. Selected sensing technologies were Global Positioning System (GPS), Radio Frequency Identification (RFID), Ultra-Wideband (UWB), Fibre Optic Sensing (FOS), pressure sensing, temperature sensing, visual sensing, and 3D scanning. The findings from this part of the thesis revealed that the most widely implemented sensing technologies in the construction industry are GPS and visual sensing (including visual recording), but even these are still not adopted by all construction companies. The remaining technologies had a lower level of adoption in the construction industry.

To find out about the factors affecting the adoption of sensing technologies in construction (ranging from the motivations to the barriers and decision making considerations), a literature review was made of the factors influencing the adoption of not only sensing technologies, but also some other similar emerging technologies in construction. Then, a mixed methods design was employed to collect quantitative data through an online survey, and qualitative data through semi-structured interviews. Partial Least Squares Structural Equation Modelling (PLS-SEM) was used for analysing the quantitative data. PLS-SEM path modelling showed the significance of 21 factors in sensing technology adoption and revealed that supplier characteristics have the highest effect on demonstrated effectiveness, then on user friendliness and affordability of the technology, and organisational culture. Moreover, demonstrative effectiveness influences technical constraints and user friendliness, organisational culture affects technical constraints, technical constraints affect user friendliness, and user friendliness influences affordability.

To support and supplement the findings of the quantitative approach, a qualitative research method was adopted to deeply investigate construction stakeholders' perceptions of sensing technologies, and the major decision making considerations they take into account for the proposal and approval of a new sensing technology implementation. Face-to-face semi-structured interviews were conducted with highly experienced construction professionals. An in-depth qualitative analysis of interview transcriptions resulted in generating themes and detailed factors that influence the adoption of sensing technologies in construction. Ultimately, a triangulation analysis of findings from the literature review, online survey and interviews resulted in the development of a governance framework that accommodated detailed factors affecting the adoption of sensing technologies in the construction industry. The purpose of the governance framework is to encourage a wider adoption and implementation of such technologies during construction processes. Seeking feedback form industry professionals, the proposed governance framework was evaluated for potential improvements and validated on its completeness, clarity and helpfulness. In addition, two secondary frameworks were developed using the same elements from the governance framework. They were the motivating framework, which demonstrated sequential motivations behind sensing technology adoption and highlighted how some barriers could be transformed into motivations, and the appraisal framework, which specified critical considerations for assessing whether a proposed sensing technology is fit for an intended purpose in construction.

Discussion of the research findings considers a comparison between the results of this study and the findings from the literature, with specific consideration of influential factors uniquely related to sensing technologies along with the factors that are common between sensing technologies and other types of digital technologies. Findings from this research indicate that the motivations that are common between the adoption of sensing technologies and other digital technologies in construction are: to improve construction performance, to have the support of the vendor or supplier, to have a user-friendly technology and to have different types of technologies integrated into one device. The findings also show that construction professionals have other motivations, uniquely related to the adoption of sensing technologies: reducing construction cost, achieving more level of effectiveness in construction practices and being independent from third parties. On the other hand, common barriers that might limit the adoption of sensing technologies just like any other digital innovation in construction include: financial constraints, skill acquisition, cultural and organisational barriers and lack of technology awareness. Whereas unique barriers towards sensing technology adoption in construction are technical barriers, safety concerns, ethical concerns and former unsuccessful experience. The overarching contribution of this research concerns the focus on the adoption of all types of sensing technologies rather than the adoption of a specific sensor or even technology adoption in general, which resulted in the development of the governance framework that can assist with the decision making process of any type of sensing technology adoption in construction.

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Abbreviations

ADC	Automated Data Collection
AVE	Average Variance Extracted
BIM	Building Information Modelling
CB-SEM	Covariance-Based Structural Equation Modelling
CCTV	Closed-Circuit Television
DCS	Digital Construction Site
ECGs	Electrocardiograms
EEGs	Electroencephalograms
FBG	Fibre Bragg Grating
FOS	Fibre Optic Sensing
GPS	Global Positioning System
HD	High Definition
ICT	Information and Communication Technology
IMUs	Inertial Measurement Units
IoT	Internet of Things
IT	Information Technology
OHS	Occupational Health and Safety
PLS-SEM	Partial Least Squares Structural Equation Modelling
PPE	Personal Protective Equipment
RFID	Radio Frequency Identification
RTLS	Real-Time Locating Systems
SEM	Structural Equation Modelling
SHM	Structural Health Monitoring
UWB	Ultra-Wideband
VIF	Variance Inflation Factor
VIM	Virtual Information Modelling
WSN	Wireless Sensor Network

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Chapter One

1

Introduction

1.1 Background

The construction industry has internationally been recognised as being an information-dependent (Martínez-Rojas, Marín and Vila 2016) and information-intensive (Behzadan et al. 2008) industry. Therefore, conventional data collection processes in this industry are labour-intensive, costly and error-prone (Shen and Lu 2012). To tackle these issues, automated data acquisition methods that use sensing technologies to provide a fortified base for ongoing monitoring of construction processes have been a focus of research during recent years (Moselhi, Bardareh and Zhu 2020).

According to the literature, deterioration in construction output could be linked to ineffective use of Information and Communication Technologies (ICT) (Odubiyi, Aigbavboa and Thwala 2019). That is why continuous data acquisition and automated monitoring of construction activities can be beneficial throughout the whole construction process in order to reduce the effects of human errors and to support planning, procurement, control, construction and management of the projects. In other words, the construction industry cannot survive without the adoption of Automated Data Collection (ADC) (Sardroud 2014), which is based on sensing technologies. Therefore, it is beneficial to adopt and implement sensing technologies as appropriate during stages of construction and on construction sites so as to improve some aspects of construction performance.

On the other hand, in order to cope with global challenges resulting from emerging technologies based on Information Technology (IT), and to keep up with other industries, the construction industry has no choice but to adapt to new changes and accommodate emerging IT-based innovations and digital technologies. This sets up the biggest motivation towards implementing a Digital Construction Site (DCS) in which sensing technologies are utilised to guarantee operational safety, employees' wellbeing, and to secure productivity and quality (Hamilton Lopes Miranda et al. 2017).

In order to better understand the definition of sensing technologies there is a need to first define a sensor. A sensor is a device that converts an input from a physical condition in the real world into an electronic signal which is converted into output that can be observed, read and interpreted by an observer, or an instrument. Therefore, sensing technologies have made it possible to collect data from the environment and use it for the intended purpose right away, or to transmit and store it for later analysis and future application. These technologies have revolutionised data collection, transmission, and analysis in almost all industries. However, the construction industry is considered to be technologically behind (Vähä et al. 2013) regarding the uptake of sensing technologies, as will be discussed in more detail in this chapter.

Sensing technologies are claimed to have great potentials in various aspects of construction management. For example, they are capable of improving:

- construction safety management (Zhang, Cao and Zhao 2017; Antwi-Afari et al. 2019)
- construction productivity through time saving in project delivery and by increasing the speed of work (Aghimien et al. 2018)
- real-time location tracking for better scheduling (Grau et al. 2009; Khoury and Kamat 2009; Park, Koch and Brilakis 2012; Turkan et al. 2012)
- construction quality control (Akinci et al. 2006; Vähä et al. 2013)
- construction activity recognition (Akhavian and Behzadan 2015)
- supply chain management (Shin et al. 2011; Hamilton Lopes Miranda et al. 2017)
- construction maintenance such as Structural Health Monitoring (SHM) (Mukhopadhyay 2011; Cao 2016), etc.

1.2 Problem Statements

1.2.1 Slow adoption of sensing technologies in construction

Reviewing the literature on ICT indicated that there are some barriers to the adoption and implementation of these technologies in construction because of various aspects, including technology, process and people related factors (Odubiyi, Aigbavboa and Thwala 2019). The construction industry lags behind other industries in the uptake of IT-based technologies (Stewart, Mohamed and Marosszeky 2004; Love, Irani and Edwards 2004; Heller and Orthmann 2014; Sepasgozar and Bernold 2013b), and digitalisation is mostly adopted during feasibility and design stages rather than the construction phase (Aghimien et al. 2018). In addition, insufficient understanding of sensing technology adoption and implementation in construction was reported in the literature (Sepasgozaar, Shirowzhan and Wang 2017).

Sensing technologies play a key role in construction automation whether in prefabrication, on-site operation or logistics, where the adoption of automation in construction was reported to be slow (Vähä et al. 2013). Likewise, Sardroud (2014) stated that even though some ADC has been applied in the construction industry, systematic implementation of these technologies in construction has been overlooked.

In the field of health and safety, there is a gap between the research of sensing and warning-based technologies and practice (Antwi-Afari et al. 2019) indicating the application of such technologies is mostly researched-based rather than being implemented or even tested in fully-scaled construction projects. In addition to that, despite a huge potential in improving construction safety performance, automated safety monitoring and analysis is neglected in task-level construction operations, according to Teizer and Cheng (2015).

In the field of construction productivity, notwithstanding the extensive research on Real-Time Locating Systems (RTLS) and their applications in construction, it is still difficult for the construction industry to adopt them in real projects as key factors have been overlooked, such as cost and deployment (Li et al. 2016). Slow adoption of Radio Frequency Identification (RFID) technology (as a powerful RTLS) in construction industry has also been reported in the literature despite its potential for improving different aspects of construction management (Lu, Huang and Li 2011).

As stated by Aghimien et al. (2018), there is a need for more research in the field of the adoption of digital technologies beyond the feasibility and design stages and more into the operation, construction and decommissioning stages. With consideration to the slow adoption of sensing technologies in construction, the **first research question** arises:

> **1.** What are the barriers to adopting innovative sensing technologies and getting benefit from their advantages during construction?

1.2.2 Insufficient information on the current status of in-use sensing technologies in real construction projects

Most of the available sensing technologies are either not implemented in real projects or are at the very early stages of being put into practice. For example, although RTLS is a group of powerful sensing technologies with huge potentials of various applications in construction, they are still at the very early stages of implementation in construction projects especially on construction sites and open areas, as only a few research studies fully implemented RTLS on real construction projects (Li et al. 2016). Therefore, little is known about the practical implementation issues such as deployment, time, cost and accuracy of sensing technologies on construction sites.

A research gap detected in a review paper on sensing and warning technologies for improving Occupational Health and Safety (OHS) on construction sites (Antwi-Afari et al. 2019) is the need to investigate the effectiveness of using sensing technologies during the total life cycle of construction projects to cover pre-construction, construction and post-construction phases. Antwi-Afari et al. (2019) identified various sensing technologies in their paper that have mostly been experimented with in laboratories, but which should be validated and applied in real construction environments. Moreover, there are gaps between existing technologies and their potentials to improve construction processes, and the extent to which these technologies are exploited in construction site management (Ozumba et al. 2019).

Thus, the literature shows there are many types of sensing technologies that have been researched, but little is known about their actual implementation in real construction projects. There is a need to identify what sensing technologies are in use in construction before going into the details of sensing technology adoption in construction. Accordingly, the **second research question** would be:

> **2.** Which sensing technologies with what degree of prevalence have already been implemented during different stages of construction practices?

1.2.3 Insufficient information on construction stakeholders' perception of sensing technologies and decision making criteria for technology adoption

Innovative technologies are recognised as key contributors to more productivity, higher safety and better quality in construction. However, the process of adopting a new technology by construction companies and factors affecting such procedures have gained little attention (Sepasgozar and Bernold 2013a).

As Odubiyi, Aigbavboa, and Thwala (2019) have indicated, a wide range of challenges in the way of effective application of IT-based technologies as well as communication technologies in construction is related to people within the construction industry. This highlights the importance of investigating the knowledge and reception of construction stakeholders towards sensing technologies in different stages of construction management and especially on construction sites.

With regard to awareness of the effectiveness of sensing technologies among construction stakeholders, a comprehensive understanding of how a new technology can effectively be utilised is without a doubt a key factor that contributes to the success of its adoption and implementation. However, this does not ensure its adoption (Goodrum et al. 2011). Lack of understanding of ADC technologies and their benefits to the construction industry is recognised to be a major barrier to the adoption of sensing technologies (Sardroud 2014).

The necessity of educating construction practitioners of sensing technologies beyond physical entities on construction sites has also been reported by Taneja et al. (2011). Construction managers, safety managers, and other key stakeholders in construction industry, could benefit from understanding how sensing technologies will improve OHS (Antwi-Afari et al. 2019). However, there is not enough information regarding construction stakeholders' perceptions and willingness to employ such technologies.

It has also been reported that a thorough understanding of the procedures by which the construction companies adopt and introduce a new technology into their system is also a critical factor to facilitate the adoption of these technologies in construction (Sepasgozar and Davis 2018). Insufficient information about the technology adoption processes in the construction industry, including the decision making practices, exists in the literature. Sepasgozar and Davis (2018) identified the need of research to investigate the process for putting a new technology into practice from the time of recognising its benefits and advantages in the construction industry.

With examples from the literature, the **third and fourth research questions** of the research became:

3. How do construction stakeholders perceive the suitability and effectiveness of sensing technologies in construction?

4. What do construction decision makers take into account during the decision-making process of adopting a new sensing technology?

1.3 Research Aim and Objectives

In order to address the research questions mentioned in section 1.2, the aim of the current research is to recognise the roots and reasons for the slow adoption of sensing technologies in the construction industry and then to investigate the motivations towards a wider adoption of these technologies. More specifically, this research ultimately intends,

To develop a framework to assist with the adoption of sensing technologies in construction.

To achieve such a goal, separate yet interrelated actions are required, ranging from reviewing the literature to finding out about the current status of sensing technologies in construction projects as well as the perception and acceptance of these technologies by key stakeholders in construction.

It is anticipated that one result of this research will be an outline of the applicability of different types of sensing technologies in construction processes and the level of their prevalence and in real construction projects. Construction stakeholders' perceptions of the effectiveness and suitability of innovative sensing technologies would impact on the adoption of such technologies in construction. Therefore, it is projected the research will develop a framework outlining major factors that affect the adoption of sensing technologies in construction to improve safety, productivity and quality in construction performance.

The research has four objectives:

Objective 1:
To obtain an in-depth understanding of the existence and applicability of sensing technologies with potential benefits for construction performance.

In order to achieve a solid base for starting data collection so as to follow a reliable path towards understanding the current status of sensing technologies in construction, there is a need to review previous research and explore the types and applications of sensing technologies that construction performance can benefit from. Therefore, the first objective of this research focuses on reviewing sensing technologies that have been identified, tested and claimed to be effective in better construction practices. Moreover, this objective includes a review of associated issues and limitations of identified sensing technologies. It is worth mentioning that some identified technologies within the literature are quite contemporary and probably have not yet been implemented in real projects. Therefore, the review of sensing technologies is regardless of their actual implementation on actual construction projects.

Objective 2:

To identify in-use sensing technologies during the construction phase in actual projects and acquire an estimate of their prevalence in order to collate against findings from the literature.

The researcher believes that it is important to have a sensible understanding and awareness of sensing technologies that are already in use in construction in order to compare them with those found through the literature review. Moreover, it would be possible to estimate their pervasiveness and the extent to which construction practices are relying on these technologies. This objective is assumed to be achievable through quantitative data collection, to provide a quantitative report on the actual use of sensing technologies in real construction projects. The combination of objectives 1 and 2 will cover the current status of sensing technologies in both construction research and the real construction world.

Objective 3:

To understand construction stakeholders' perceptions of sensing technologies, affiliated effectiveness, benefits and barriers, as well as major factors influencing sensing technology adoption in construction.

This objective is assumed to identify the most important deliverables of the current research and is envisaged to lead to the next objective and ultimate aim of this research. In this objective, factors affecting the adoption of sensing technologies in construction will be investigated through construction stakeholders' perceptions of such technologies and their suitability for construction practices. In this regards, construction stakeholders' perceptions of sensing technologies will be investigated to extract the factors they believe can affect the implementation of these factors in construction.

This objective is achievable firstly through an extensive literature review and then by data collection, with direct inquiry of key construction stakeholders who are experienced in using sensing technologies and who also have hands-on decision making experiences regarding innovative technology adoption. The data will be analysed to find out which factors significantly influence the adoption of sensing technologies in construction projects, which factors are taken into account while nominating and approving the adoption and introduction of a new sensing technology into existing construction practices, and what changes this adoption impose on existing systems and practices.

Objective 4:

To develop a framework assisting with the process of new sensing technology adoption into the construction practices, highlighting motivations towards a wider adoption along with barriers and concerns that need to be addressed.

The fourth objective, which is in line with the ultimate aim of this research, will expand the findings from the previous objectives to generate a framework that depicts the benefits of implementing a new sensing technology while properly addressing all major concerns and constraints. Such a framework is expected to prepare a pathway for wider adoption of sensing technologies in the construction industry. This objective is achievable by including into the framework all important factors discovered throughout the research. Objectives 3 and 4 are about factors affecting the adoption of sensing technologies in construction.

1.4 Significance and Contribution of the Research

This research was designed to provide an understanding of the current status of sensing technologies in the construction industry and facilitate the adoption process of such technologies during construction. The significance of the current research study can be shown from three angles.

First, objectives 1 and 2 articulate collective information on the current status of sensing technologies both in construction research and in real construction projects. In other words, the first two objectives of this research make an effort to look at various types of sensing technologies that are claimed to be effective in construction within the literature (objective 1) and those that are adopted by the industry and are already implemented in real construction projects (objective 2) and analyse their convergence or divergence. Combining the results from these two objectives will assist with a better understanding of the extent to which the construction industry has responded with the outcome of research into sensing technology. Another outcome will be to identify the barriers to adopting innovative sensing technologies in construction and contribute to a better alignment between research endeavours and industry-specific needs for new sensing technologies.

Second, the significance of objective 3 is undeniable as it is dedicated to the discovery of influential factors in sensing technology adoption in construction through construction stakeholders' perception; after all, the attitude of construction staff and management plays an important role in innovation technology adoption (Odubiyi, Aigbavboa and Thwala

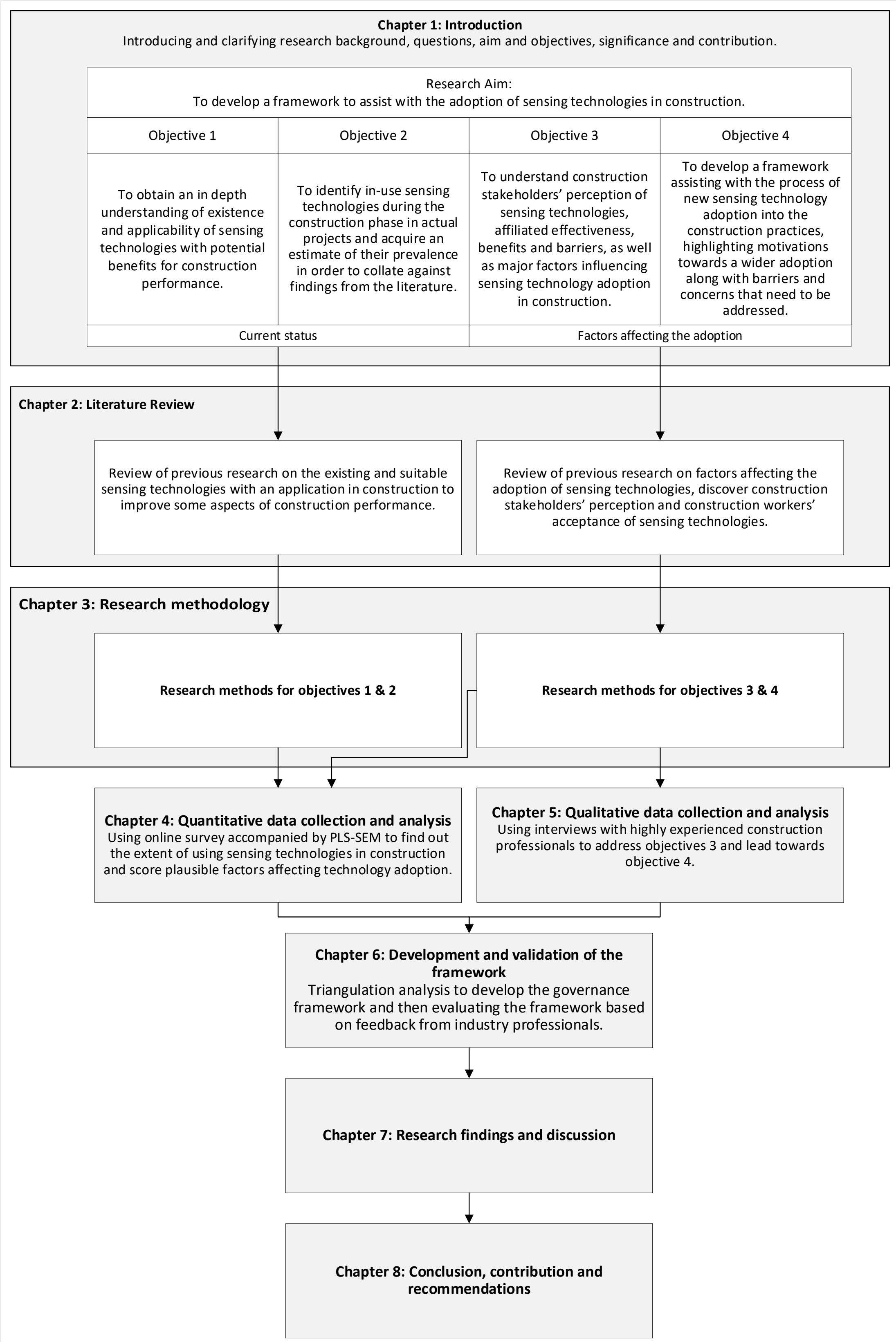
2019). Addressing this objective will help to identify the barriers to sensing technology adoption as well as stakeholders' motivations towards the adoption of such technologies in construction. Sardroud (2014) emphasised the necessity of further research regarding ADC technology adoption and implementation in the construction industry, based on the perception of these technologies among construction professionals. It is worth mentioning that several studies investigated the adoption of IT-based technologies or ICT in construction, but the literature is scarce in the field of sensing technology adoption in construction (Sepasgozaar, Shirowzhan and Wang 2017). Therefore, the main contribution of this research is a focus on the adoption of sensing technologies in construction, and factors affecting the implementation of such technologies by referring to major factors reported for other types of technologies, and examine them to determine if they also apply to sensing technology adoption. Besides, the results of the qualitative analysis of semi-structured interviews will be related to the applicability and suitability of sensing technologies in construction.

Third, the development of the governance framework is considered significant as it highlights the benefits of using sensing technologies, motivations towards adopting them, decision making considerations and construction-specific expectations from an effective sensing technology, while specifying identified barriers to deal with before the adoption process. The principal contribution of this research is achieved when the governance framework is validated by industry feedback.

1.5 Organisation of Thesis

Figure 1.1 depicts the flow of the eight chapters of this thesis.

Figure 1.1 *Structure of the thesis*



Chapter 1 is an introductory chapter with general information about the background of this research, and it also declares the research questions and defines the research aim and objectives. This chapter also clarifies the significance and contribution of this research and depicts the structure of the thesis.

Chapter 2 is dedicated to the literature review of sensing technologies in construction research. Chapter 2 is designed to cover two aspects: the current status of sensing technologies in construction, and factors affecting the adoption of such technologies by the construction industry. The first part of Chapter 2 reviews previous research of the types, applications, benefits and limitations of sensing technologies in construction. These technologies might or might not have been implemented in real projects, but they have been claimed to be effective in order to improve some aspects of construction performance being safety, quality or productivity. Various sensing technologies have been recognised in the literature with discussion of their application and aspects of construction performance they can improve. The second part of Chapter 2 is devoted to construction stakeholders' perceptions and workers' acceptance of sensing technologies to identify major factors influencing the adoption of such innovations in the construction industry. Motivations towards the adoption and implementation of sensing technologies, perceived benefits and suitability of sensing technologies and barriers restricting their adoption in construction practices have been reviewed.

Chapter 3 is allocated to the research methodology. It provides details of the philosophical standpoints of this research. Moreover, the design of the research methods is outlined and the most suitable method for each of the four objectives is explained. Methods of data collection used in this research are then justified by comparison with previous research studies in similar areas.

Chapter 4 discusses the quantitative data collection and analysis ranging from the design of an online survey for quantitative data collection and its distribution, to analysing responses using Structural Equation Modelling (SEM). This chapter provides descriptive reporting of the current status of sensing technologies in construction to fully address objective 2. Some major factors identified in the literature were examined for sensing technology adoption through Partial Least Squares Structural Equation Modelling (PLS-SEM). Results of the PLS-SEM path modelling in this chapter range from significant factors to supported hypotheses representing the relationships between factors.

Chapter 5 describes the qualitative part of data collection through face-to-face semi-structured interviews with highly experienced construction stakeholders who are experienced with sensing technologies in construction as well as being involved in the decision making process for adopting new technologies. Qualitative data analysis is accomplished using NVivo Pro software. Thematic analysis of interview transcriptions identified factors that construction professionals believe have the most influence on sensing technology adoption.

Chapter 6 undertakes a triangulation analysis to develop the governance framework. The framework was presented to industry professionals for their feedback on the completeness, clarity and helpfulness of the framework. The feedback from the industry professionals is used to improve and validate the framework. Moreover, two secondary frameworks are extracted from the validated governance framework to highlight more specific aspects of the governance framework.

Chapter 7 is allocated to the summary of the research findings and discussion on the main contributions of the study. The findings for each of the four research objectives are summarised in this chapter. Different components of the governance framework (which is the main outcome and contribution of the current research) are discussed and argued against. The present study and previous research in similar areas are analysed to determine any conformity or contrast between their findings.

Chapter 8 concludes the thesis and discusses the contribution, limitations and practical implications of the research. Recommendations for future research are also provided in this chapter.

1.6 Summary

As an introduction to this research and the structure of the thesis, this chapter has first presented a background to the research. It then has provided details about the necessity of the research, declared the research questions, and proposed the research aim and objectives that will address research questions. The significance of the research and its contributions to the body of knowledge are also provided in this chapter. Finally, a brief introduction to the whole structure of the thesis was presented, outlining how the research is reported throughout the chapters of this thesis.

Chapter Two

2

Literature Review

2.1 Introduction

The first part of this chapter reviews the literature to identify the most popular types of sensing technologies in construction management research that were reported to be effective in improving construction performance. That review will meet the first objective of the research, which is to achieve an in-depth understanding of existing sensing technologies and their applications in construction. This section will lead to the second objective, investigating the extent to which such technologies have been implemented in construction projects.

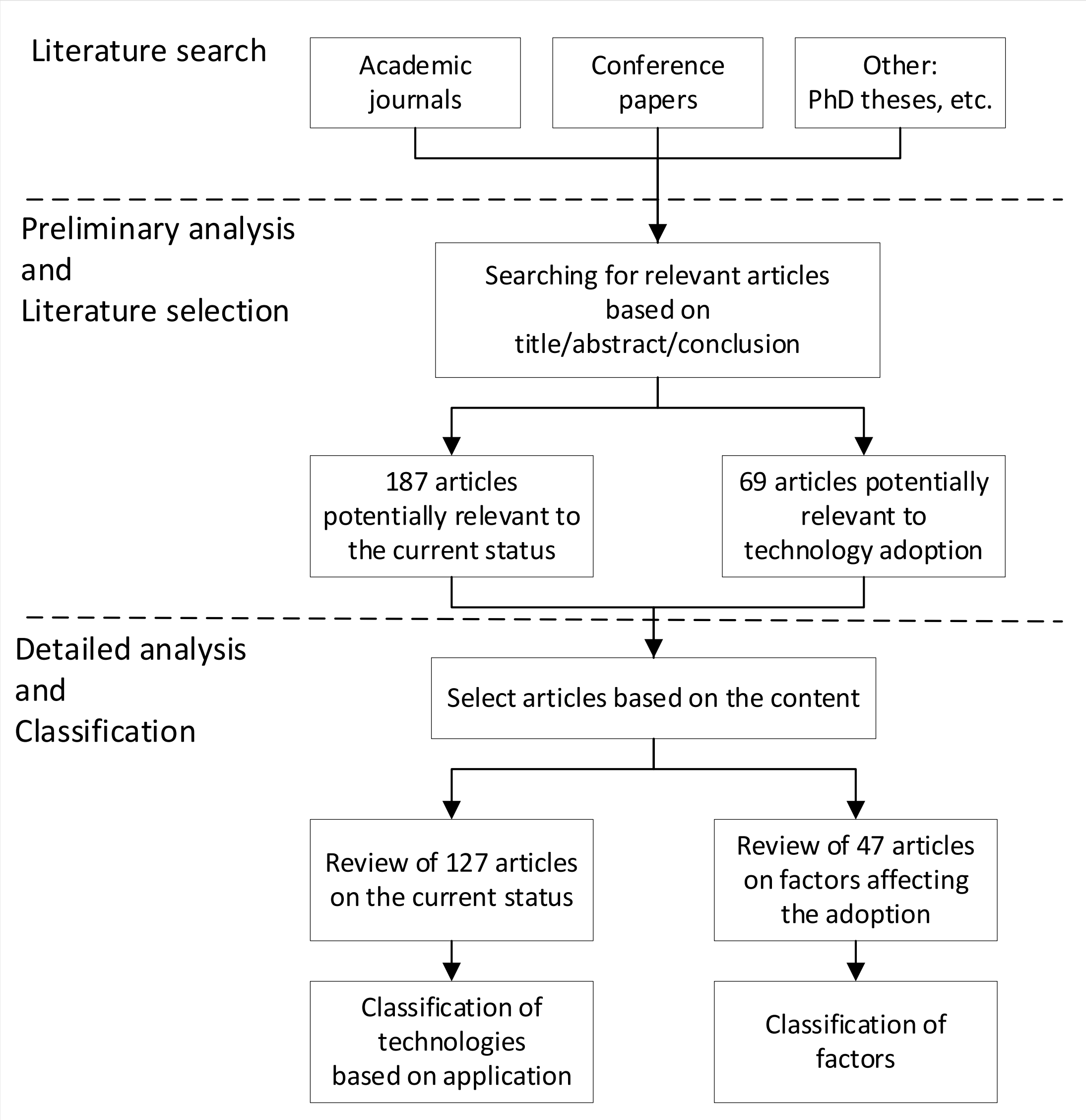
The second part of this chapter reviews the literature that has investigated construction stakeholders' perceptions of sensing technologies, and reports the factors that research has found to affect the adoption of sensing technologies in construction. These factors range from motivations and benefits to barriers and challenges associated with introducing such innovative technologies into construction processes. Such factors point to reasons that have prevented the construction industry from the uptake of sensing technologies because, although such technologies are increasingly researched, the construction industry has been slow to adopt and implement the technologies in real construction projects and on construction sites (Stewart, Mohamed and Marosszeky 2004; Love, Irani and Edwards 2004; Heller and Orthmann 2014). This part of the literature review will constitute the first step towards the third objective of this research and will establish a solid point of data collection for this research.

2.2 Methods and Material for Literature Review

The method used for the literature review took place in seven sequential steps. These steps are "*scope definition and clarification*", "a *literature search*" to find potentially relevant resources, "a *preliminary literature analysis*" and "*relevant literature selection*" to identify and shortlist relevant literature, "*detailed literature analysis*" to extract related materials, "*classification of the findings*" for the sake of easy reporting and finally, "*reporting the results*".

The seven steps followed for the literature review are explained in Research Methods, section 3.4.1. The scope definition and clarification as well as time span for each part of the literature review in this chapter are explained below. Figure 2.1 shows the process followed for the literature review in this chapter and also specifies the number of articles identified and shortlisted for both the current status of sensing technologies in construction and the factors affecting their adoption. Of 187 potential articles on types of sensing technologies and their applications in construction, 127 were selected to classify technologies based on their applications. Of 69 articles relevant to the adoption of technology, 47 were subsequently analysed to identify factors affecting the adoption of sensing technologies in construction.

Figure 2.1 *Method for literature review*



2.2.1 Scope definition and clarification

The first part of the literature review was dedicated to the current status of sensing technologies in construction. The research scope was to identify potential sensing technologies applicable to construction management and practices that would improve either safety, productivity or quality of construction projects.

Various types of sensing technologies have been studied, reviewed and tested in the literature, but this present review considers only those that are suitable for improving some aspects of construction performance and which can be used for regular measurement or monitoring. In other words, sensors used only for testing purposes were excluded from this research since testing is usually a requirement and not an ongoing process to improve construction performance. The reason for this decision is to differentiate between automated regular data collection that could be beneficial to improve construction performance and testing, which is a necessity and usually a prerequisite to the start of a process. For example, sensors used for geotechnical investigations or localisation of underground services at the early stages of a construction projects were not included in this research.

In regards to the second part of this chapter which focuses on the factors affecting the adoption of identified sensing technologies in construction, the scope of the literature review extended beyond sensing technology adoption, because the adoption of sensing technologies is a contemporary phenomenon in the construction industry and the literature is scarce on this subject (Sepasgozaar, Shirowzhan and Wang 2017). Therefore, the literature review in the second part of this chapter embraces a review of factors that affect the adoption and implementation of ICT, ADC and IT-based technologies as well as other similar innovative technologies in construction research such as Building Information Modelling (BIM), 3D printing, etc.

2.2.2 Time span of literature reviewed

The review was of research articles on sensing technologies and their applications in construction that were published in 2009 and onwards, with a few exceptions being published before 2009. The reason for choosing such a timeframe was that the majority of research studies were less than a decade old, although a few research articles investigating the use of sensors to improve the construction performance were older than 20 years and with limited applicability, such as Miller and Bernold (1991) proposal for a sensor integrated nailing system to increase construction productivity.

In construction safety monitoring and measurement, as an important and crucial field of construction management, few sensor-based technologies with restricted application were found in the literature before 2005. Likewise, only after 2009 were considerable numbers of articles related to using sensors in construction safety management published each year (Zhang, Cao and Zhao 2017). Moreover, according to a review on the application of RTLS in construction safety by Soltanmohammadlou et al. (2019), the number of related articles published per year increased significantly from 2011 to 2012. They reported only one research paper on this subject prior to 2009 and from 2009 to 2011 only three papers per year were published. A similar trend was reported by Antwi-Afari et al. (2019), which was that only two articles on sensing and warning technologies in construction OHS were published per year during the period 2007 and 2008. Three or four papers were published in 2010–2011 and then the publications doubled in 2012.

Hence for this literature review of the types of sensing technologies and their applications in construction, research articles mainly published during and after 2009 were reviewed with a few exceptions for outstanding studies published before 2009.

For the second part of this chapter no time restriction was imposed for the publication of literature because construction research of sensing technologies is quite recent, thus there is little history of their adoption in construction. Besides, much of the literature in this field was published during the last decade so, naturally, the previous time span was also applied to the literature review on factors affecting the adoption of sensing technologies in construction. However, some older articles investigating the adoption of other technologies in construction have also been used.

2.3 Current Status of Sensing Technologies in Construction Research

Popular sensing technologies in the construction research area which were reported to be capable of improving some aspects of construction performance have been identified throughout the literature. The research-based studies either tested these technologies in laboratory tests or in case studies, which means they were not necessarily adopted in real, on-site projects.

A major consideration before studying the current status of sensing technologies in construction was knowing that some level of integration of multiple sensor-based technologies is usually required to meet the ever-growing requirements of modern construction management because of the complexity and dynamic nature of construction projects (Zhang, Cao and Zhao 2017). In this present review, mostly individual technologies and their applications in construction were considered. Sensing technologies introduced in this chapter are most likely to be applicable beyond what is explained here, however that is beyond the scope of this present research. For example, some sensing technologies might also be applicable during the design stages or for testing purposes before the start of the construction phase. Such applications are excluded in this chapter for being outside the scope of the current research.

In this part of the literature review, identified technologies were classified and reported according to their applications in any of the following areas in construction management: construction safety, quality and productivity. Each category is broken down into sub-categories later in this chapter.

2.3.1 Sensing technologies to improve construction safety

The importance of safety in the construction industry is unquestionable as a result of the high rate of work-related injuries and risk associated with the industry. According to Safe Work Australia, 401 workers died on construction sites in Australia in the 10 years from 2003 to 2013 (Safe Work Australia May 2015). Sensing technologies in this regard have a great potential to improve safety on construction sites and mitigate safety risks, which is evident through the increasing number of publications researching the application of sensors and sensor-based technologies in construction safety management during recent years. However, there is still a long way to go from theoretical research to practical application in real projects of sensing technologies for construction safety management (Zhang, Cao and Zhao 2017).

Various types of sensing technologies have been reported to be effective and efficient in real-time construction safety management. A review paper classified sensor-based technologies in construction safety management to be either location-based or vision-based sensing technologies or Wireless Sensor Network (WSN) based technologies (Zhang, Cao and Zhao 2017). In this chapter, the same classification is used to review the most common sensing technologies in each category with applications to improve construction safety management.

2.3.1.1 Location-based sensing

Location-based sensing technologies, also known as Real-Time Locating Systems (RTLS) are usually based on wireless technologies such as Wi-Fi, Bluetooth, Global Positioning System (GPS), Radio Frequency Identification (RFID) or Ultra-Wideband (UWB). RTLS have proven to be effective in construction process management, safety management and on-site resource management through locating and tracking construction materials and resources (Li et al. 2016). In other words, effective management practices along with RTLS technologies can decrease safety risks on construction sites at an operational level. However, such systems still have some shortcomings such as limited signal strength through obstructions, high cost, and low accuracy in some cases (Zhou, Whyte and Sacks 2012).

RTLS can supplement safety management with accurate and efficient remote monitoring of real-time localisation and tracking of construction resources to detect unsafe behaviours, predict movements and therefore prevent accidents (Soltanmohammadlou et al. 2019). It is also effective in increasing situational awareness for construction site workers (Cheng and Teizer 2013) and for crane operators (Cheng and Teizer 2014), quantitative hazard exposure analysis (Luo et al. 2016), and even in behaviour-based safety (Heng et al. 2016). The literature review found the most common location-based technologies for improving construction safety were GPS, RFID, and UWB.

GPS

GPS is a radio navigation system that uses information received from satellites and provides powerful capabilities for positioning and locating purposes. GPS is reported to be the most prevalent location-based sensing technology nowadays (Martínez-Rojas, Marín and Vila 2016). GPS technology has great potential to be used in different aspects of construction safety management such as identifying unsafe proximity detection (Wang and Razavi 2016), proximity detection of workers on foot and construction equipment (Teizer and Cheng 2015), construction equipment monitoring (Zekavat, Moon and Bernold 2014b), increasing situational awareness of on-site workers (Cheng and Teizer 2013), identifying construction resources (Majrouhi Sardroud 2012; Taneja et al. 2011), improving tower crane navigation systems (Lee et al. 2012), and construction equipment activity recognition (Akhavian and Behzadan 2015).

However, any technology has some limitations and challenges. Delays in processing and transmission of data, low performance in congested areas and signal blockage in indoor environments are associated with the use of GPS for location tracking on construction sites (Moselhi, Bardareh and Zhu 2020).

RFID

RFID is an identification technology that uses radio waves to read and capture digital data encoded in RFID tags. RFID technology is capable of identifying and tracking construction materials and equipment in real time without any direct contact or requiring line-of-sight, which makes it more efficient and desirable compared to traditional barcode systems (Sun, Jiang and Jiang 2013).

An RFID system usually consists of a reader (or an antenna), radio frequency tags which are attached to items that need to be tracked, and a software system that manages collected information. RFID tags can be active or passive. An active tag has a built-in power source which enables the tag to transmit data on its own. Passive tags are more popular as they are smaller and less expensive than active tags but they should be activated by an RFID reader before transferring data. In other words, passive tags reflect the radio signals transmitted from the reader. Moreover, passive tags have shorter readability distances than active tags, although both can be read outside the line-of-sight which is a significant capability of RFID technology.

RFID technology has been identified as the most popular sensing technology among all RTLS research studies in the literature (Li et al. 2016), although its adoption is still slow in the construction industry (Sun, Jiang and Jiang 2013; Lu, Huang and Li 2011). RFID technology is also quite effective in indoor construction localisation where satellite position information is not available (Razavi, Montaser and Moselhi 2012).

Construction research is beginning to discover the benefits and effectiveness of location tracking with RFID technology in reducing safety risks on construction sites for the following purposes:

- preventing accidents and collision (Chae and Yoshida 2010; Yang et al. 2012; Brilakis, Lee and Becerik-Gerber 2013; Ding et al. 2013)
- proximity detection alert systems (Teizer et al. 2010; Marks and Teizer 2013)
- access controls of workers and vehicles to specific positions (Wu et al. 2010; Kanan, Elhassan and Bensalem 2018)

- helping workers to change their risky behaviour (Zhou and Ding 2017)
- storage of safety information (Wu et al. 2010)
- indoor localisation of mobile (Fang et al. 2016) and stationary (Ko 2010) construction resources
- locating construction workers to send early warning alerts (Kwang-Pyo et al. 2014).

However, some limitations might restrict the use of RFID in construction such as accuracy and simultaneous identification of multiple tags, range issues due to obstructions, especially in the case of metal obstacles and also in humid environment (Moselhi, Bardareh and Zhu 2020).

UWB

UWB technology is another type of remote location tracking and sensing technology that uses high-bandwidth radio communications. UWB has been used in identifying and locating dynamic hazard zones (Teizer and Cheng 2015), collision avoidance (Zhang and Hammad 2012), increasing situational awareness of construction workers and equipment operators (Cheng and Teizer 2013) and crane operators (Hwang 2012; Zhang, Hammad and Rodriguez 2012). It also has been used to enhance construction safety training (Teizer, Cheng and Fang 2013).

UWB is a powerful technology in construction resource and material tracking, and is attracting the interest of researchers because its performance has been analysed in indoor construction sites (Maalek and Sadeghpour 2013), harsh environments (Cheng et al. 2011) and indoor job-sites with the presence of construction related obstructions (Shahi et al. 2012). UWB has been found to show better performance than other types of RTLS in indoor environments (Alarifi et al. 2016), even in cases where wooden materials have blocked signals, however metal blockage reduces the performance of UWB to locate and track construction material (Shahi et al. 2012).

The use of UWB in construction is also affected by some limitations such as range issues over long distances, missing data, possible calibration difficulties, and limited update rates (Moselhi, Bardareh and Zhu 2020).

2.3.1.2 Vision sensing and laser scanning

Various types of vision sensing and laser scanning technologies are available to construction management to employ in order to improve construction safety, ranging from well-established technologies such as photographs and video recordings, to more contemporary technologies such as laser scanning.

Laser scanners (3D scanners) are active sensors capable of capturing detailed geometries of physical items and their environmental conditions in minutes. Laser scanners work through a rotating laser photon source, both vertically and horizontally, that emits laser signals to measure the distances between the objects and their photon source with high accuracy (Taneja et al. 2011). Laser scanners have mostly been used for capturing 3D models (Sepasgozaar, Shirowzhan and Wang 2017), but they still have more applications in construction safety management such as increasing situational awareness of crane operators (Cheng and Teizer 2014), simulating virtual construction sites and workers training environment (Cheng and Teizer 2013), data collection of operation processes and monitoring the workflow of construction activities (Taneja et al. 2011). Despite the many benefits, this technology is not suitable for scanning and modelling moving objects, nor for providing information about colours, textures and materials. Other limitations include requiring a clear line-of-sight for scanning, long data processing time and high capacity for data storage (Moselhi, Bardareh and Zhu 2020).

Another type of vision-based sensing device applicable to monitor and improve construction safety performance is Kinect which contains multiple infrared sensors to capture body skeleton images in order to detect workers' postures on construction sites (Yu et al. 2017), and for motion capture and action recognition when monitoring construction workers (Han et al. 2013; Han and Lee 2013).

Last but not least, 2D and 3D imaging and video recordings are vision-based sensing technologies effective in construction safety performance by assisting with decision making in construction operations (Teizer 2008; Taneja et al. 2011), blind lifts of tower crane operations (Lee et al. 2012) and robust communication between project network and work-front operations (Zekavat, Moon and Bernold 2014a).

2.3.1.3 Wireless Sensor Networks

WSN, depending on their intended purpose of use, can be a network of various types of sensors integrated into a system and wirelessly communicating with each other and with central data recording devices. Most of the sensors applied in the form of a WSN in construction safety management include temperature sensors, displacement sensors, light sensors, pressure sensors and Fibre Optic Sensing (FOS) (Zhang, Cao and Zhao 2017).

Emergence of WSN technology has fulfilled hundreds of potential applications in construction such as infrastructure data collection, site safety and security monitoring, construction operation monitoring and tracking (Ibrahim and Moselhi 2014), monitoring the presence of workers on site, access control to restricted areas and proper Personal Protective Equipment (PPE) wearing (Naticchia, Vaccarini and Carbonari 2013), material and resource tracking in indoor areas (Shen and Lu 2012) and establishing an improved communication platform for tower crane operations (Zekavat, Moon and Bernold 2014a). Likewise, automated monitoring of construction processes for improving health and safety and enhancing construction maintenance is also achievable through employing WSN as demonstrated by Shin et al. (2014) who designed and tested a WSN configured of cracking and vibration sensors for a bridge monitoring case study.

FOS is a technology usually employed in a form of WSN that can measure temperature, strain or pressure as well as some other quantities by transmission of light through an optical fibre. FOS is completely immune to electromagnetic interference and capable of functioning in hostile surroundings. Fibre optic sensors are user-friendly devices with an elevated sensitivity which makes them suitable for detecting crack damage in concrete structures (Afzal, Kabir and Sidek 2012). Fibre Bragg Grating (FBG) sensors, as a type of FOS, are effective in the field of environmental health monitoring such as temperature measurement for real-time temperature monitoring of frozen soil (Ye, Ni and Yin 2013; Ding et al. 2013), as well as structural health monitoring such as strain and displacement measurement of tunnel segments in underground construction (Ding et al. 2013).

2.3.2 Sensing technologies to improve OHS in construction

Occupational Health and Safety (OHS) is a major division of construction safety management in which sensing technologies can contribute to remarkable improvement. A review by Antwi-Afari et al. (2019) pointed out that sensing and warning-based technology was not frequently researched before 2007, but since then the number of published research articles regarding OHS in the construction industry has increased annually. An exponential surge in the number of research articles on sensing and warning technologies in construction OHS since 2016 (Antwi-Afari et al. 2019) indicated that sensing technologies were increasingly recognised as potentially effective measures to improve construction OHS in recent years.

Various types of sensing technologies are suitable for OHS depending on the jobsite characteristics and requirements. This could simply be images from Closed-Circuit Television (CCTV) (Mneymneh, Abbas and Khoury 2017), video cameras (Zhu et al. 2016; Han and Lee 2013), range cameras (Ray and Teizer 2012) and even built-in sensors of smart phones (Nath, Akhavian and Behzadan 2017). The intentions behind employing vision-based sensing technologies (as noted above) were to improve OHS through detecting whether workers use hard hats by:

- using object detection methods (Mneymneh, Abbas and Khoury 2017)
- predicting workers' movements (Zhu et al. 2016)
- identifying construction workers' unsafe behaviour (Han and Lee 2013)
- motion detection (Han et al. 2013) and posture estimation and classification (Ray and Teizer 2012)
- identifying potential bodily work-related ergonomic risks (Nath, Akhavian and Behzadan 2017).

OHS can also benefit from other types of sensing technologies such as RFID technology in detecting and checking the presence and compliance of PPEs on construction sites (Kelm et al. 2013; Barro-Torres et al. 2012). They also include a wide range of wearable sensors and environmental sensors as discussed next.

2.3.2.1 Wearable sensors

In recent years an interesting area has emerged in construction research involving the application and benefits of wearable sensing technologies to improve some aspects of safety performance in construction management including OHS. Although wearable sensing devices can also improve construction productivity, Jacobs et al. (2019) reported that improving safety increases positive willingness for using wearable sensing technologies than promoting productivity.

With the aim of improving safety in the workplace, many researchers investigated the compatibility and adaptability of wearable devices in construction activities in order to collect value-adding information to either mitigate hazards or enhance construction workers' wellbeing. However, the adoption of wearable sensors in construction is in its rudimentary stages as opposed to other industries (Awolusi, Marks and Hallowell 2018).

Wearable devices could simply be available devices on the market such as smart watches (Guo et al. 2017) and wristbands (Kamišalić et al. 2018) which integrate various types of sensors in one wearable device for real-time and non-invasive monitoring of workers' health, or more specific devices for collecting particular data such as heart rate and heart rate variability in the form of a chest sensor (Lee et al. 2017).

Wearable sensing technologies can have various applications in construction safety management as well as OHS and construction workers' wellbeing programs. Some examples of the areas in which wearable sensing technologies can make a considerable improvement are:

- detecting abnormal situations via human activity recognition (Mukhopadhyay 2015)
- developing early warning systems to safeguard workers' wellbeing (Yi et al. 2016)
- preventing fatalities and accidents (Kanan, Elhassan and Bensalem 2018; Awolusi, Marks and Hallowell 2018)
- real-time monitoring of physical fatigue in workers (Aryal, Ghahramani and Becerik-Gerber 2017)
- measuring workers' psychological status and reducing unsafe behaviours on site (Guo et al. 2017)
- environmental sensing such as detecting chemicals and gases on site (Awolusi, Marks and Hallowell 2018).

Motion sensors

Inertial Measurement Units (IMUs) are among the most common motion sensors to detect construction workers' awkward postures (Chen, Qiu and Ahn 2017), gait abnormalities (Yang et al. 2017) and fall-risk assessment (Jebelli, Ahn and Stentz 2016).

Accelerometers are also a group of motion sensors effective for detecting falls (Mukhopadhyay 2015), identifying potential work-related ergonomic risks (Nath, Akhavian and Behzadan 2017) through body posture sensing and analysis and monitoring if helmets are worn properly by construction workers (Sung Hun et al. 2018).

Physiological sensors

Physiological wearable sensing devices have the potential to be effective in OHS through measuring and monitoring construction workers' health factors. Different areas have been recognised in which physiological wearable sensors can be of assistance such as mental and emotional wellbeing, physical workload and fatigue monitoring, muscle activity monitoring to prevent musculoskeletal disorders and posture detection to prevent falling (Ahn et al. 2019).

Many types of physiological sensors are tested and reported to be effective in noted areas of safety and wellbeing management:

In the area of monitoring mental and emotional health of construction workers, electroencephalograms (EEGs) which track and record brain wave patterns were used to monitor stress levels (Jebelli, Hwang and Lee 2018a), mental fatigue (Jebelli, Hwang and Lee 2018b), emotional states (Hwang et al. 2018) and attention level (Wang et al. 2017; Jebelli, Hwang and Lee 2017) in construction workers for the purpose of obtaining a base for investigating and addressing any psychological problems of construction workers and, therefore, avoid unsafe behaviours.

Regarding the monitoring of heart rate and its variability in construction workers, electrocardiograms (ECGs) which detect and measure electrical activities of heart in the form of chest sensors were used to monitor on-duty and off-duty physical activities of construction roofers (Lee et al. 2017). Wristband-type heart rate monitoring devices were also used to capture any significant variations in physical demands (Hwang and Lee 2017; Kamišalić et al. 2018), to estimate energy expenditure and metabolic equivalents (Lee et al. 2017), and to track heart rate as a measure to evaluate the heat strain level in construction workers in hot and humid environment (Yi et al. 2016). Likewise, ECG along with EEGs and infrared temperature sensors were employed for real-time monitoring of physical fatigue in construction workers (Aryal, Ghahramani and Becerik-Gerber 2017).

Electrical activities of construction workers' muscles can be measured using surface electromyography in order to monitor spinal biomechanics of a construction workforce exposed to repetitive lifting tasks (Antwi-Afari et al. 2017) and rebar tying while squatting and sitting in low positions (Umer et al. 2017).

Integrated sensors in PPE

A wide range of wearable sensing technologies consist of one or a few different types of sensors inserted or attached to PPE to monitor safety risks and health measures depending on jobsite requirements. For instance, automated remote monitoring of PPE on construction sites was approached by Dong, Li, and Yin (2018) through the use of pressure sensors and RTLS to assess whether the PPE was worn properly. A more specific case is when three-axis accelerometers were attached to construction workers helmets to monitor if their helmet was being worn and if it was being worn properly (Sung Hun et al. 2018).

Another outstanding example of different sensors integrated into a system and attached to PPE was the work of Adjiski et al. (2019) who proposed a prototype system in which hard hats and safety glasses were equipped with sensors and connected to smartphones and smartwatches through Bluetooth technology. The types of sensors used in this prototype included: gas sensors, dust sensors, sound sensors, smoke sensors, temperature sensors, accelerometers, gyroscopes, magnetometers, heart rate sensor measures and High Definition (HD) and infrared cameras. Although proposed to be implemented during mining operations, the same concept can apply to underground construction operations.

2.3.2.2 Environmental sensors

Sensing technologies that can measure and monitor different types of environmental characteristics can also be effective in OHS practices. The literature review detected different types of environmental sensing with an application during the construction phase, including dust sensors for fine particle concentration monitoring (Naticchia et al. 2014) and for protecting workers against excessive respirable dust on construction sites (Smaoui et al. 2018) and temperature sensors such as wet bulb globe temperature which accommodates for the effects of air temperature, humidity, wind speed and solar radiation on humans and is considered to be the most widely used environmental index for monitoring and managing occupational heat stress (Yi et al. 2016).

2.3.3 Sensing technologies to improve construction quality

Construction quality control is another area in which sensing technology might be beneficial. In this regard, those sensing technologies that can be applicable in construction quality management are reviewed in this section.

FOS and FBG

FOS and FBG technologies can have various applications in construction quality controls. FOS has proven to be effective in monitoring temperature and stress/strain variation of reinforced concrete structures during construction (Song et al. 2017). Moreover, an effective real-time and convenient quality control method for asphalt mixture compaction operation was established using FBG technology during lab experiments (Yiqiu et al. 2014).

RFID

RFID technology is also reported to be effective in construction quality controls by helping with better monitoring of concrete curing progress (Moon, Zekavat and Bernold 2017) and material quality assurance (Lu, Huang and Li 2011).

Temperature sensing

Temperature sensors are effective in real-time measurement and continuous monitoring of the internal temperature of in-place concrete structures during the early curing stages (Lee et al. 2014), and to assess the strength of cast-in-place concrete (Akinci et al. 2006).

Laser scanning

The interest in using laser scanners as a contemporary image processing technology is increasing to address the need for acquisition of highly accurate 3D images of buildings and the built environment and have been used to acquire 3D building geometries (Sepasgozaar, Shirowzhan and Wang 2017).

Laser scanners have the potential to be used for quality assessment of precast concrete in order to prevent failure of precast concrete elements during construction (Kim et al. 2015) as well as assuring the quality of prefabrication processes and identifying deviations of prefabricated modules from the design (Chi et al. 2015).

2.3.4 Sensing technologies to improve construction productivity

Improving construction productivity through better scheduling, cutting back on construction time and cost and reducing construction waste has always been of interest to construction managers. It has been reported by previous researchers that real-time progress reporting of construction activities can overcome productivity issues such as cost overruns or scheduling delays, therefore the employment of remote sensing technologies has been proposed to achieve a more automated data acquisition platform rather than relying on manual labour-intensive and time-consuming systems (Moselhi, Bardareh and Zhu 2020).

In this section, various applications for popular sensing technologies in the field of improving construction productivity are reviewed.

GPS

GPS technology has many potential uses, such as resource localisation and tracking of materials to increase construction productivity (Chi et al. 2015; Razavi and Haas 2011; Grau et al. 2009). More specifically, such tracking is used to collect real-time information about the current status of a delivery fleet (Zekavat, Moon and Bernold 2014b) and to provide real-time travel data of concrete delivery trucks to reduce productivity loss and idleness (Rahnamayiezekavat et al. 2014). Likewise, position tracking of construction key personnel was also achieved through using indoor GPS in order to save some cost and time (Khoury and Kamat 2009). Automated tracking of construction resources is beneficial in construction productivity monitoring, which is possible predominantly by using GPS and RFID technologies (Soleimanifar 2011).

RFID

RFID technology can have various applications to increase construction productivity. Examples are:

- applications in time and schedule management (Sun, Jiang and Jiang 2013; Olatunji and Akanmu 2014)
- supply network visibility (Young et al. 2011)
- asset management and supply chain management (Shin et al. 2011; Wang et al. 2016; Moon et al. 2018)
- operational cost saving in precast construction supply chain (Wang, Hu and Zhou 2017)
- material localisation, monitoring and tracking (Kim et al. 2011; Razavi and Haas 2012; Chi et al. 2015; Razavi and Haas 2011; Grau et al. 2009)
- automatically updating progress reports (Zekavat, Moon and Bernold 2014a; Razavi, Montaser and Moselhi 2012)
- active and accurate information flow between material planning, procurement, warehouse, construction site and material monitoring staff (Ren, Anumba and Tah 2011)
- identification of construction material and resources (Majrouhi Sardroud 2012; Taneja et al. 2011)
- construction waste management and machinery maintenance records (Lu, Huang and Li 2011).

Besides, RFID technology in combination with ultrasound signals will provide higher accuracy for construction asset tracking (Skibniewski and Jang 2009).

UWB

As well as construction safety performance, construction productivity can also benefit from UWB technology by:

- determining real-time 3D resource localisation (Teizer, Venugopal and Walia 2008)
- location tracking of construction staff (Khoury and Kamat 2009)
- construction equipment tracking (Siddiqui, Vahdatikhaki and Hammad 2019)
- more productive training sessions (Teizer, Cheng and Fang 2013)
- in combination with wearable accelerometers to assess construction workers' activities (Cheng et al. 2013).

Vision-based sensing

Monitoring and tracking construction resources, which was mentioned as a core function to improve construction productivity, is also achievable using video cameras (Park, Koch and Brilakis 2012; Park, Makhmalbaf and Brilakis 2011). On the other hand, 3D laser scanning technology in combination with schedule information has been reported to result in more effective and efficient tracking of construction progress than manual progress tracking of construction processes (Turkan et al. 2012).

Vision-based sensing technologies have also been used along with some other technologies for a more robust accuracy in material tracking and localisation especially in congested and indoor construction sites (Moselhi, Bardareh and Zhu 2020). Examples are the integration of photogrammetry with RTLS such as GPS (Song et al. 2015) and robotic total stations (Siu, Lu and AbouRizk 2013), as well as incorporation of video recording with UWB (Siddiqui 2014).

Wearable sensors

Wearable sensing technologies can also be effective in measuring construction workers' productivity by exploring the relationship between the physiological status of workers and their productivity (Mao et al. 2018) or location tracking for effective planning and control (Awolusi, Marks and Hallowell 2018). However, there is a greater willingness to use wearable sensing technologies in construction for safety purposes rather than productivity improvement (Jacobs et al. 2019).

2.3.5 Automation in construction

Automation of construction processes is basically founded on sensing technologies. GPS has been identified in the literature as the main technology for automation processes in construction. Rossi et al. (2019) proposed a system to improve the process monitoring of construction machinery by real-time recognition of individual activities of construction equipment through embedding a smart plug (that consisted of GPS, power sensors and Wi-Fi) with a micro controller which would monitor the equipment activities and correct the operation if necessary. They tested their proposed system on three types of construction machinery, namely: a sawing machine, a concrete mixer and a hoist.

Employing autonomous machinery and equipment is also feasible using a combination of different sensing technologies. These types of unmanned equipment are quite conventional in the mining industry but still not adopted in the construction industry. Underground mining has benefited from automated control technologies through employing a variety of sensing technologies for charging blast holes using laser scanners (Bonchis et al. 2014), rock drilling using UWB and laser positioning systems (Li and Zhan 2018), as well as underground scraping using laser positioning systems (Li and Zhan 2018; Chi, Zhan and Shi 2012).

2.4 Factors Affecting the Adoption of Sensing Technologies in Construction

In order to promote the adoption of sensing technologies in construction projects it is necessary to explore the process of adopting a new technology in the construction industry. According to Sepasgozar (2015), the process of technology adoption in construction industry occurs through three consecutive stages: first is to identify new technologies; second, to gain knowledge about existing options; and third, to compare those options. These three stages identify the features, attributes, advantages, and disadvantages of identified technologies which will enable comparison between nominated options.

Although the literature on sensing technologies acknowledges that different aspects of construction performance can be affected positively by employing relevant sensing technologies, limited evidence refers to their implementation in real projects. For example, Hamilton Lopes Miranda et al. (2017) reported that the application of sensing technologies in a digital construction site aims at guaranteeing sustainable environments, safe operations, and employees' wellbeing, as well as for increasing productivity, profitability and quality of processes. However, such digital construction sites are still not implemented because of challenges such as integrating demands with data collection and the need of promoting technical innovations. The implication is that there are some barriers which inhibit the implementation of sensing technologies in construction.

Although many research studies explored, investigated and verified the applications and capabilities of sensing technologies in construction (as summarised in section 2.3), many barriers to the adoption of such technologies have been recognised and reported in the literature. Moreover, the extent to which construction decision makers perceive the benefits and effectiveness of sensing technologies in order to improve construction performance also influences the adoption of such technologies by construction companies. Therefore, this present review of major factors influencing the adoption of sensing technologies in construction is of two major categories: construction stakeholders' perceptions and construction workers' acceptance of sensing technologies.

2.4.1 Construction stakeholders' perceptions of emerging technologies

The decision making process for adopting a new technology by the construction industry is affected by the attitude of managers towards technology (Mitropoulos and Tatum 1999). In other words, it is well-established that the perception of top managers plays an essential role in the uptake of innovation.

An understanding of stakeholders' perceptions of sensing technologies and their perspectives towards the benefits and challenges regarding the implementation of such emerging technologies in construction is important for a more efficient adoption of technology, because raising awareness about the benefits, capabilities and effectiveness of new technology in construction will contribute to improved adoption processes (Usman and Said 2012; Hong et al. 2016). Resistance towards accepting a new technology is often caused by insufficient understanding and exposure to it (Alreshidi, Mourshed and Rezgui 2017) yet, in contrast, an understanding of market condition and technology capabilities can increase managerial confidence about the success of decision making (Mitropoulos and Tatum 1999).

Slow adoption of sensing and IT-based technologies in construction was also evident through stakeholders' perceptions of such technologies. A study on South African construction professionals' perceptions of digitalisation in construction has shown that digitalisation is helpful with time management, productivity and document quality but mostly at design and feasibility stages rather than during construction (Aghimien et al. 2018). Therefore, since sensing technology has not yet been fully adopted into the construction industry, or its implementation is still at a rudimentary stage during construction, it is worth reviewing literature that explores the construction stakeholders' perceptions of other technologies such as IT, ICT and ADC, or basically any digital technology that has been introduced as an innovation to the construction industry, an example being BIM. Hence from here on, the scope of the literature review was expanded beyond sensing technologies and included previous research studies on almost any type of innovative digital technology in order to extract as much information as possible.

Research into construction stakeholders' perceptions has been of different areas such as exploring acceptance, adoption, benefits, barriers and impacts of various innovations and emerging technologies in the construction industry. Examples of such technologies are:

- ICT (Usman and Said 2012; Ikediashi and Ogwueleka 2016; Akinbile and Oni 2016; Redwood et al. 2017; Amusan et al. 2018; Odubiyi, Aigbavboa and Thwala 2019)
- web-based systems (Doloi 2014), ADC (Sardroud 2014)
- wireless technologies (Heller and Orthmann 2014)
- BIM (Rogers, Chong and Preece 2015; Lee, Yu and Jeong 2015; Hong et al. 2016; Alreshidi, Mourshed and Rezgui 2017)
- IT (Sweis et al. 2015; Yang, Wang and Sun 2018; Dithebe et al. 2019)
- 3D scanning (Sepasgozaar, Shirowzhan and Wang 2017)
- Virtual Information Modelling (VIM) (Didehvar et al. 2018)
- digitalisation (Aghimien et al. 2018; Sepasgozar and Davis 2018)
- 3D printing (Wu et al. 2018)
- remote sensing (Moselhi, Bardareh and Zhu 2020).

Although most articles in this area have focused on top management perceptions of the importance of technology and its adoption, Sepasgozar and Davis (2018) confirmed that not only top managers are involved in the decision making process of acquiring a new technology, but engineers and operating crews are also consulted. Moreover, interaction and collaboration between the suppliers and end users was reported to play a fundamental role in the technology adoption process (Sepasgozar and Davis 2018) as supplier marketing can affect perceived innovation characteristics such as compatibility, trialability, complexity and uncertainty (Frambach and Schillewaert 2002).

Previous research studies reviewed here have in the main adopted some types of qualitative or quantitative data collection methods (in the form of surveys, interviews, focus group discussions, case studies, etc.) to understand construction stakeholders' perceptions of emerging technologies. The purpose of those studies and the methods employed was to extract factors affecting the adoption of technologies in the construction industry, and to prioritise which factors are more important and which challenges need to be addressed first. Regarding what construction stakeholders perceive about the applicability and suitability of digital technologies in construction, the literature has confirmed the effectiveness of adopting new technologies in construction such as ICT technologies from the points of view of contractors, despite some shortfall in people's interest in using such technologies (Usman and Said 2012).

Research on construction stakeholders' perceptions of various types of digital technologies identified many benefits and challenges regarding the implementation of such technologies in construction projects. For example, Akinbile and Oni (2016) and Amusan et al. (2018) reported that Nigerian construction companies can improve productivity by using ICT, however they will face challenges regarding the cost and budget, training, lack of skilful staff and inadequate power supply. Likewise, using VIM as a novel ICT was reported to create huge benefits in project integration management in construction, although some challenges would also arise especially regarding required changes in project organisation and staff expertise when the project team is not ready for upcoming changes (Didehvar et al. 2018). More detailed benefits and barriers identified through construction stakeholders' perceptions of emerging digital technologies in the literature are discussed in sections 2.4.1.1 and 2.4.1.2.

2.4.1.1 Benefits of and motivations towards adopting sensing technologies in construction

A positive attitude towards new technologies affects the decision making process of new technology adoption (Mitropoulos and Tatum 1999). Raising awareness about the benefits and effectiveness of sensing technologies in different areas of construction management can create a positive attitude and motivate construction decision makers to consider employing sensing technologies as the same motivation has been reported for the adoption of BIM (Hong et al. 2016) and ICT (Usman and Said 2012) in construction. Hence, because of the need to discover which factors will persuade construction stakeholders to employ sensing technologies in order to improve construction performance, it is worth looking into factors motivating the construction industry to adopt other types of innovations and digital technologies.

One significant motivation to employ new IT-based technologies in the construction industry was reported to be the advantage of becoming more competitive in the market (Mitropoulos and Tatum 2000) which is crucial to small and middle-sized construction companies (Hong et al. 2016). However, this motivation reduces over time as more companies employ the same technology reduce any advantage. There are other motivations behind new technology adoption by construction companies. For example, the adoption of technology might be problem-driven, solution-driven or forced by external requirements such as the request of clients, or compliance with regulations (Mitropoulos and Tatum 2000; Hong et al. 2016). In many of such cases, the possible benefits of employing the new technology play an important role in decision making processes for the adoption of technology.

Hong et al. (2016) claimed that technology awareness along with organisational and individual innovativeness (organisational support and individual acceptance) would highly influence technology adoption. Hence it is expected that raising awareness about the benefits, applicability and competency of sensing technologies in construction as well as being exposed to such technologies, might contribute to a straightforward and efficient adoption process. In fact, the same strategy was reported for using ICT for construction site management (Usman and Said 2012).

A review of the literature revealed that construction professionals are to some extent aware of the benefits of digital technologies in construction. The following benefits are raised by construction professionals regarding the use of digital technologies in construction.

- Cost reduction (Goodrum et al. 2011; Doloi 2014; Alizadehsalehi and Yitmen 2018; Ahmed et al. 2018).
- Time saving and improved productivity (Doloi 2014; Akinbile and Oni 2016; Schall, Sesek and Cavuoto 2018; Aghimien et al. 2018; Alizadehsalehi and Yitmen 2018; Goodrum et al. 2011).
- Process improvement and improved performance (Heller and Orthmann 2014; Ozorhon and Oral 2017; Ahmed et al. 2018).
- Error minimisation (Doloi 2014; Heller and Orthmann 2014).
- Increased information (Heller and Orthmann 2014; Akinbile and Oni 2016).

– Better monitoring (Heller and Orthmann 2014), better facilities management (Heller and Orthmann 2014).
– Improved leadership and decision support systems (Ozorhon and Oral 2017; Ahmed et al. 2018; Alizadehsalehi and Yitmen 2018).
– Reduced risk of injury and illness (Schall, Sesek and Cavuoto 2018).
– Increase in employees' wellness and satisfaction (Schall, Sesek and Cavuoto 2018).
– Better document quality (Aghimien et al. 2018).
– Improved quality of construction project delivery (Sweis et al. 2015; Alizadehsalehi and Yitmen 2018).

Table 2.1 summarises the benefits from the implementation of different types of innovative digital technologies in the construction projects as identified in the literature review.

Table 2.1 *Benefits of digital technologies in construction according to construction stakeholders*

Benefit	**Reference**
Cost reduction	(Goodrum et al. 2011; Doloi 2014; Alizadehsalehi and Yitmen 2018; Ahmed et al. 2018)
Time saving and improved productivity	(Doloi 2014; Akinbile and Oni 2016; Schall, Sesek and Cavuoto 2018; Aghimien et al. 2018; Alizadehsalehi and Yitmen 2018; Goodrum et al. 2011)
Process improvement and improved performance	(Heller and Orthmann 2014; Ozorhon and Oral 2017; Ahmed et al. 2018)
Error minimisation	(Doloi 2014; Heller and Orthmann 2014)
Increased information	(Heller and Orthmann 2014; Akinbile and Oni 2016)
Better monitoring	(Heller and Orthmann 2014)
Better facilities management	(Heller and Orthmann 2014)
Improved leadership and decision support systems	(Ozorhon and Oral 2017; Ahmed et al. 2018)
Reduced risk of injury and illness	(Schall, Sesek and Cavuoto 2018; Häikiö et al. 2020)
Increase employees' wellness and satisfaction	(Schall, Sesek and Cavuoto 2018; Häikiö et al. 2020)
Better document quality	(Aghimien et al. 2018)
Improved quality of construction project delivery	(Sweis et al. 2015; Alizadehsalehi and Yitmen 2018)

2.4.1.2 Barriers to the adoption of sensing technologies in construction

The slow adoption of sensing technologies in construction could be due to many barriers preventing effective implementation. Aside from the fact that the nature of construction projects are fragmented and temporary (Sardroud 2014), many more challenges have been identified throughout the literature regarding the adoption of digital technologies in construction by looking into stakeholders' perceptions about such innovations. One classification separates identified challenges in information and communication technologies into three broad categories related to technology, process and people (Odubiyi, Aigbavboa and Thwala 2019) while another study on the implementation of automated data collection technologies classified the barriers into cost-related, process-related and technology-related issues (Sardroud 2014).

Since a wide range of barriers in the adoption of ICT in construction was reported to be related to people and attitude of staff and management (Odubiyi, Aigbavboa and Thwala 2019), it is necessary to identify and understand the factors that construction stakeholders and decision makers perceive as "barriers" and "challenges". Through such understanding, it is possible to identify solutions and address the challenges to technology adoption.

As a major barrier, capital cost of implementation has been noted repeatedly (Goodrum et al. 2011; Sardroud 2014; Alreshidi, Mourshed and Rezgui 2017; Amusan et al. 2018; Alizadehsalehi and Yitmen 2018; Dithebe et al. 2019; Odubiyi, Aigbavboa and Thwala 2019; Olaniyan 2019; Alfar 2016). Other cost-related impediments towards technology adoption in construction include training costs and the high cost of employing professionals (Akinbile and Oni 2016; Alreshidi, Mourshed and Rezgui 2017; Amusan et al. 2018; Ahmed et al. 2018), maintenance costs (Goodrum et al. 2011; Dithebe et al. 2019; Sardroud 2014), operating costs (Goodrum et al. 2011) and uncertainty about the cost benefit relationship (Sardroud 2014; Schall, Sesek and Cavuoto 2018; Amusan et al. 2018).

Aside from cost-related barriers, there are challenges related to people involved in technology adoption and implementation such as:

- lack of interest and resistance to change (Usman and Said 2012; Alreshidi, Mourshed and Rezgui 2017; Didehvar et al. 2018; Olaniyan 2019)
- lack of understanding or sufficient information about the suitability and benefits of the system (Sardroud 2014; Alreshidi, Mourshed and Rezgui 2017; Alizadehsalehi and Yitmen 2018)

- lack of well-trained staff or adequate training (Sardroud 2014; Rogers, Chong and Preece 2015; Akinbile and Oni 2016; Alreshidi, Mourshed and Rezgui 2017; Didehvar et al. 2018; Amusan et al. 2018; Alizadehsalehi and Yitmen 2018; Dithebe et al. 2019; Olaniyan 2019)
- legal and ethical concerns regarding privacy, confidentiality, security and ownership of data (Usman and Said 2012; Alreshidi, Mourshed and Rezgui 2017; Schall, Sesek and Cavuoto 2018; Häikiö et al. 2020)
- compliance by employees (Schall, Sesek and Cavuoto 2018)
- organisational barriers and company culture (Sardroud 2014; Golizadeh et al. 2019; Olaniyan 2019; Adriaanse, Voordijk and Dewulf 2010)
- restrictive regulation or lack of government support (Golizadeh et al. 2019; Olaniyan 2019; Rogers, Chong and Preece 2015).

Different types of technical and technological complications and difficulties were also identified in the literature to negatively affect the adoption and implementation of innovative technologies in construction. Among those are:

- lack of integrity, durability, reliability and technology immaturity (Sardroud 2014; Schall, Sesek and Cavuoto 2018; Dithebe et al. 2019; Golizadeh et al. 2019; Odubiyi, Aigbavboa and Thwala 2019)
- operational difficulties and lack of purposely made devices for construction sites (Usman and Said 2012)
- lack of proper IT infrastructure or software compatibility (Sardroud 2014; Didehvar et al. 2018; Ahmed et al. 2018)
- data management issues such as massive data input and storage (Alreshidi, Mourshed and Rezgui 2017; Ahmed et al. 2018)
- power supply issues (Usman and Said 2012; Heller and Orthmann 2014; Akinbile and Oni 2016; Odubiyi, Aigbavboa and Thwala 2019).

There are, of course, more barriers to the introduction of emerging technologies to construction processes such as fragmented and temporary nature of construction projects (Adriaanse, Voordijk and Dewulf 2010), site-related complications (Golizadeh et al. 2019), challenges resulting from change in the process (Didehvar et al. 2018) and good manufacturing practice requirements (Schall, Sesek and Cavuoto 2018) which are not related to any of the above-noted categories but still affect technology adoption. Table 2.2 summarises the barriers towards the adoption of different types of digital technologies in construction projects as identified in the literature review.

Table 2.2 *Barriers to digital technology adoption in construction according to construction stakeholders*

Barrier	Reference
Cost-related	
Implementation cost	(Goodrum et al. 2011; Sardroud 2014; Alreshidi, Mourshed and Rezgui 2017; Amusan et al. 2018; Alizadehsalehi and Yitmen 2018; Dithebe et al. 2019; Odubiyi, Aigbavboa and Thwala 2019; Olaniyan 2019; Alfar 2016)
Cost of training or employing professionals	(Akinbile and Oni 2016; Alreshidi, Mourshed and Rezgui 2017; Amusan et al. 2018; Ahmed et al. 2018)
Cost of maintenance	(Goodrum et al. 2011; Dithebe et al. 2019; Sardroud 2014)
Operating cost	(Goodrum et al. 2011)
Uncertain cost-benefit relation	(Sardroud 2014; Schall, Sesek and Cavuoto 2018; Amusan et al. 2018)
People-related	
Lack of interest or resistance to change	(Usman and Said 2012; Alreshidi, Mourshed and Rezgui 2017; Didehvar et al. 2018; Olaniyan 2019)
Lack of understanding or insufficient information	(Sardroud 2014; Alreshidi, Mourshed and Rezgui 2017; Alizadehsalehi and Yitmen 2018)
Lack of well-trained staff or inadequate training	(Sardroud 2014; Rogers, Chong and Preece 2015; Akinbile and Oni 2016; Alreshidi, Mourshed and Rezgui 2017; Didehvar et al. 2018; Amusan et al. 2018; Alizadehsalehi and Yitmen 2018; Dithebe et al. 2019; Olaniyan 2019)
Compliance of employees	(Schall, Sesek and Cavuoto 2018)
Company culture	(Adriaanse, Voordijk and Dewulf 2010; Sardroud 2014; Golizadeh et al. 2019; Olaniyan 2019)
Restrictive regulation or lack of government support	(Golizadeh et al. 2019; Olaniyan 2019; Rogers, Chong and Preece 2015)
Legal or ethical concerns	(Usman and Said 2012; Alreshidi, Mourshed and Rezgui 2017; Schall, Sesek and Cavuoto 2018; Häikiö et al. 2020)
Technology-related	
Technology immaturity	(Sardroud 2014; Schall, Sesek and Cavuoto 2018; Dithebe et al. 2019; Golizadeh et al. 2019; Odubiyi, Aigbavboa and Thwala 2019)
Operational difficulties	(Usman and Said 2012)
Lack of proper IT infrastructure or lack of software compatibility	(Sardroud 2014; Didehvar et al. 2018; Ahmed et al. 2018)
Data management issues	(Alreshidi, Mourshed and Rezgui 2017; Ahmed et al. 2018)
Power supply issues	(Usman and Said 2012; Heller and Orthmann 2014; Akinbile and Oni 2016; Odubiyi, Aigbavboa and Thwala 2019)

Barrier	Reference
Other barriers	
Site-related issues	(Golizadeh et al. 2019)
temporary nature of construction	(Adriaanse, Voordijk and Dewulf 2010)
Change in the process	(Didehvar et al. 2018)
Manufacturing requirements	(Schall, Sesek and Cavuoto 2018)

2.4.2 Construction workers' acceptance of sensing technologies

The level of acceptance of sensing technologies among construction workers is an influential factor in technology adoption since user acceptance and trust-building are reported to be the two key components to the adoption of Internet of Things (IoT)-based technologies in OHS (Häikiö et al. 2020). While managerial support affects employees' intentions to accept a new system (Sargent, Hyland and Sawang 2012), not only are managers involved in technology adoption decisions, but also engineers, operating crews and fitters, all of whom are usually consulted before the adoption (Sepasgozar and Davis 2018). In addition, compliance by employees affects successful technology adoption when data is collected from employees (Schall, Sesek and Cavuoto 2018). Hence, it is quite beneficial, if not crucial, to seek the acceptance and reception of construction workers towards sensing technology especially in regards to adopting wearable technologies since it involves personal interaction with data collection devices.

Construction workers' acceptance of an emerging technology has been investigated for IT adoption (Sargent, Hyland and Sawang 2012), mobile computing devices (Son et al. 2012), IoT-based safety monitoring (Häikiö et al. 2020), integration of Augmented Reality and BIM (Elshafey et al. 2020), and wearable sensing technologies (Choi, Hwang and Lee 2017; Jacobs et al. 2019; Mettler and Wulf 2018).

Many previous research studies, especially those regarding the use of wearable technologies, reported that privacy, security and confidentiality are major concerns held by construction workers (Choi, Hwang and Lee 2017; Häikiö et al. 2020; Schall, Sesek and Cavuoto 2018) and users show a higher level of willingness to accept and use wearable sensors if data is only collected during working hours (Jacobs et al. 2019) in order to keep personal and business matters separate (Mettler and Wulf 2018). Meanwhile, the top motivation of construction workers to accept wearable sensing technologies was reported to have the opportunity to identify health risks and promote occupational safety (Häikiö et al. 2020; Jacobs et al. 2019). Jacobs et al. (2019) suggested that companies considering the implementation of wearable sensors should reassure their employees of the effectiveness of wearable devices while involving and informing them of the processes for technology selection and implementation.

"Perceived usefulness" and "perceived ease of use" are the two concepts that dominate the literature on the construction workers' acceptance of innovative technologies. These two concepts, which have been driven from a technology acceptance model (Davis 1985), are usually studied from a psychological point of view to understand users' acceptance (Sepasgozar and Davis 2018).

2.4.2.1 Perceived usefulness

According to Davis (1989), perceived usefulness of a system is defined as the extent to which users believe that such a system will assist them to achieve a higher level of performance. Perceived usefulness has been used as a determining factor for technology adoption in the context of construction research (Goodrum et al. 2011; Son et al. 2012; Lee, Yu and Jeong 2015; Hong et al. 2016; Yang, Wang and Sun 2018; Sepasgozar and Davis 2018). The concept of perceived usefulness could be determined by various factors such as social influence, job relevance and top management support (Son et al. 2012) as well as direct and indirect benefits at the organisational level (Hong et al. 2016).

Perceived usefulness has been recognised as a motivation towards using emerging technologies such as BIM (Hong et al. 2016), scanner technology (Sepasgozaar, Shirowzhan and Wang 2017) and wearable sensing technologies (Choi, Hwang and Lee 2017; Jacobs et al. 2019) in the construction industry.

2.4.2.2 Perceived ease of use

Perceived ease of use of a system is the degree to which the user believes that they can use a system effortlessly and free from difficulties (Davis 1989). Perceived ease of use has been used as a determining factor for technology adoption in the context of construction research (Goodrum et al. 2011; Son et al. 2012; Lee, Yu and Jeong 2015; Sepasgozar and Davis 2018; Elshafey et al. 2020; Hong et al. 2016). Perceived ease of use is usually measured through different variables such as training and technological complexity (Son et al. 2012).

Perceived usefulness and perceived ease of use are the top determinants of user acceptance (Davis 1989) as are contributing factors to construction workers' reception of sensing technologies (Choi, Hwang and Lee 2017), although user satisfaction is more influenced by perceived usefulness than perceived ease of use (Son et al. 2012).

As the application of wearable sensors is quite new in construction research, several studies suggest that it is important to bear in mind the acceptance of state-of-the-art technologies by construction workers. Choi, Hwang, and Lee (2017) investigated this matter to identify factors influencing the adoption of wearable sensing technologies by construction workers especially regarding the use of a smart vest with an embedded GPS for location tracking, and a wristband for physiological monitoring. They discovered that “perceived usefulness”, “social influence”, “perceived privacy risk” and “perceived ease of use” were the major factors that determine workers’ acceptance of wearable devices.

2.5 Summary

This chapter investigated the theoretical background of the present research by reviewing the literature on the applicability of sensing technologies in construction as well as the perceptions of these technologies by construction stakeholders.

The literature review initially focused on identifying the most common sensing technologies that can be applied to improve construction safety performance, OHS, quality or productivity. The most-noted types of sensing technologies that were reported to be applicable and effective in construction were identified and reviewed. Outstanding applications of identified sensing technologies were reviewed along with relative advantages and limitations of each, regarding their suitability to be employed on construction sites and in construction activities. The majority of applications for sensing technologies identified in the literature were focused on construction safety performance, inter alia, RTLS and WSN were the two broad categories of sensing technologies that were claimed to be widely applicable in construction. While reviewing the literature, a wide range of recent research studies on the effectiveness of wearable sensing technologies and their possible applications in construction were identified and reviewed to support wellness programs and promote OHS on construction sites.

The literature review then identified and discussed factors affecting the decisions of construction stakeholders to adopt such technologies including affiliated benefits of sensing technologies, motivations towards employing them, and barriers preventing from their implementation during construction practices. Identification of factors in this literature review went beyond the adoption of sensing technologies and also embraced the factors influencing the adoption of other types of innovative digital technologies such as ICT, ADC, VIM, BIM, 3D printing, etc. In this chapter, these factors were classified in two broad categories of the benefits and the barriers of sensing technologies in construction. Identifying these factors provided a base for designing data collection material for further investigation and discussion on their significance in regard to sensing technology adoption and implementation in construction.

Furthermore, construction workers' acceptance of new sensing technologies was also an interesting subject of research, especially with regard to personal data collection or using wearable sensors when the new technology implementation involves data collection from individuals. Evidence from the literature indicated that perceived usefulness and perceived ease of use are the two critical factors for the construction workers' acceptance of such technologies.

Chapter Three

3

Research Methodology

3.1 Introduction

Methodology is considered to be the theory of organisation of an activity. In other words, it is the totality of methods to perform an active interaction of a human being with an external environment (Novikov and Novikov 2013). Research methodology is therefore a system of methods that defines principles and procedures of doing research (Fellows and Liu 2015) and a set of ontological and epistemological assumptions that forms the basis of research (Mir and Watson 2000). Research methods on the other hands are tools or techniques by which data is collected and analysed (Fellows and Liu 2015).

In this chapter, the philosophical standpoints of this present research are explained and then the approaches, methodological choices, research strategy and the research methods to conduct the study are clarified.

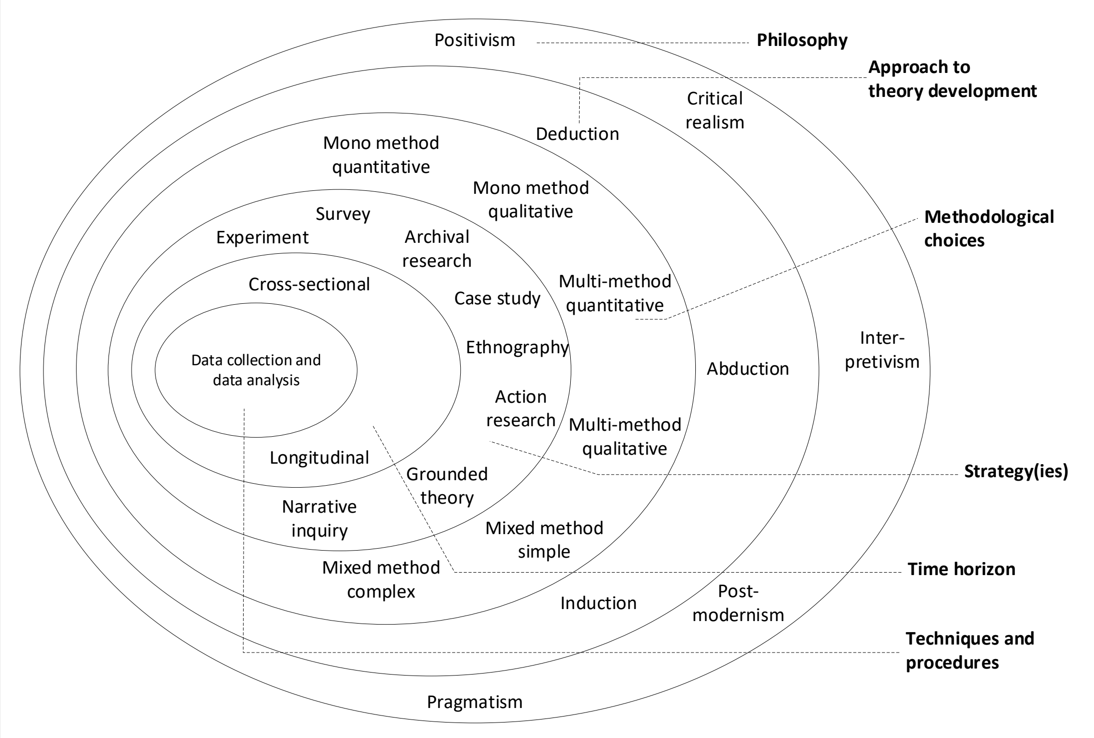
3.2 Research Philosophy

As methodology is the philosophical foundation of a research, there is a need to specify the research philosophy of this thesis. It is necessary to do so as philosophical assumptions have inevitable impacts on understanding the research and taking valid steps through data collection methods as well as data analysis and interpretation. Research philosophy refers to a system of beliefs that deals with the nature and source of research knowledge. In other words, research philosophy defines the approaches, methods, strategies and tools with which the data will be collected and analysed (Saunders, Lewis and Thornhill 2015). According to Saunders, Lewis, and Thornhill (2015), research philosophy is the outmost layer in the "research onion" (see Figure 3.1). The philosophy and subsequent methodological aspects of a research activity should be clarified before defining the choice of methods for data collection and analysis (Saunders, Lewis and Thornhill 2015).

Three characteristics of research philosophy explain the basis for aspects of the present study and selection of research methods. These three characteristics of research philosophy are ontology, epistemology and axiology. Ontology clarifies the nature of reality, epistemology discusses the theory of knowledge and axiology refers to the theory of values in a research.

Figure 3.1 *The research Onion*

Source: ©2015 Mark Saunders, Philip Lewis and Adrian Thornhill



3.2.1 Ontology

Ontology is associated with existence or being (Fellows 2009) and assumptions about the nature of reality which governs how a researcher sees the world around them (Saunders, Lewis and Thornhill 2015). Ontology deals with the questions regarding the nature of research, whether it is conceived of as objective or subjective to social factors. Accordingly, two main ontological positions are objectivism and subjectivism. Objectivism (also known as positivism) depicts an ontological position in which social entities are existent in reality, irrelevant to and independent from social factors concerned with their existence (Saunders 2012). Whereas subjectivism (also known as interpretivism) observes social phenomenon based on perceptions from social factors, meaning such perceptions are socially constructed and may change. In subjectivist ontology, the reality is considered multiple as seen through different views (Creswell 2018b).

Regarding the aim and objectives of this thesis, the nature of the current research study is subjective because of professionals' insights and awareness towards the current status, benefits and applications of sensing technologies in construction, as well as the researcher's analytical skills and interpretation. Therefore, the philosophy of this research is based on subjectivism indicating that there are different social realities (opinions, beliefs and experiences) for different social entities (respondents/interviewees). Ontological assumptions of this research indicate the reality is socially constructed. This imposes a constant state of change and revision to the social phenomenon under study. In other words, it is assumed that the nature of the reality being investigated is socially constructed through culture and language. It engages multiple meanings, interpretations and realities, therefore changes in processes, experiences and practices are very likely (Saunders, Lewis and Thornhill 2009).

3.2.2 Epistemology

The methodology of scientific research is often viewed as a branch of epistemology. Epistemology, as a sub-discipline of modern philosophy, studies the laws, stages, forms, methods and means of processing knowledge (Novikov and Novikov 2013) and is associated with theories of knowledge which attempt to answer the questions about the nature of knowledge, its limits and how researchers can acquire it (Fellows 2009) as well as the relationship between the knower and the known (Klenke 2016). In other words, epistemology deals with topics such as the ways that the reality can be investigated and acknowledged through them plus principles and attributes that guide the process of getting to know the reality (Irene Vasilachis de 2009).

Epistemological assumptions of a research study influence the way that the data is understood and interpreted and must be consistent with ontological views adopted in the research (Klenke 2016). According to Jha (2008), two fundamental epistemological requirements for research should clearly and openly be acknowledged: the researcher's assumptions of what counts as knowledge and the methods that are driven from them.

According to the subjectivism philosophy of this research, it is assumed that narratives, perceptions, interpretations, opinions and experiences of people counts as knowledge and the researcher is eager to enter the social world of the research participants and understand the world from their points of view. As the result, the two epistemological requirements of the research have been addressed: the perception of professionals in the construction industry is valued knowledge, and the research methods to gain such knowledge should accommodate direct inquiry to attain quality data that will be interpreted and formed into knowledge.

3.2.3 Axiology

Axiology discusses the role of values and ethics in research and how the researcher will deal with their own values and values of participants (Klenke 2016; Saunders, Lewis and Thornhill 2015). Axiology also deals with the questions related to what is valuable and desirable for humans and societies. In this regard, values can be intrinsic, extrinsic or systemic (Biedenbach and Jacobsson 2016). A researcher's choice of philosophy and choice of data collection methods are reflections of their axiology through what philosophy or methods they value over other options (Saunders, Lewis and Thornhill 2015).

Moreover, axiology refers to the values and aims for which the research was conducted, meaning whether the researcher's aim was either to predict something or only understand it and what they value in research methods and findings (Lee and Lings 2008). Two types of axiological goals underlying research methodology are terminal and instrumental goals. The former refers to the ultimate aim of a specific research study and the latter discusses the criteria by which a particular research study would be evaluated (Patterson and Williams 1998). This present research is value-bound as the researcher's judgement and interpretation skills have undeniable impact on the research (Saunders, Lewis and Thornhill 2009).

3.3 Inductive Approach to Theory Development

There are three approaches to theory development: deductive, inductive, and abductive approaches. A deductive approach usually starts with a theory and uses logical reasoning to make conclusions from a set of information to test an existing theory. The inductive approach, on the other hand, uses collected data to explore a phenomenon and generate a conceptual framework (Saunders, Lewis and Thornhill 2015). The third approach, abductive, begins with a "surprising fact" and then improvises a plausible theory of how this could have occurred. Data collection is firstly used to explore a phenomenon, identify themes and locate it in a conceptual framework. Then, subsequent data collection is used to test the framework, with the possibility of moving back and forth with these steps as more surprising facts might be uncovered (Saunders, Lewis and Thornhill 2009).

The reasoning approach to the current research is inductive as it starts with data collection in order to understand the current status of sensing technologies in real construction projects and of course to investigate the reasons behind the reported slow adoption. Inductive reasoning will guide this research from the construction stakeholders' perceptions of sensing technologies (observation) to comprehending whether or not sensing technologies are suitable for a construction environment (theory) presented in the form of a conceptual framework.

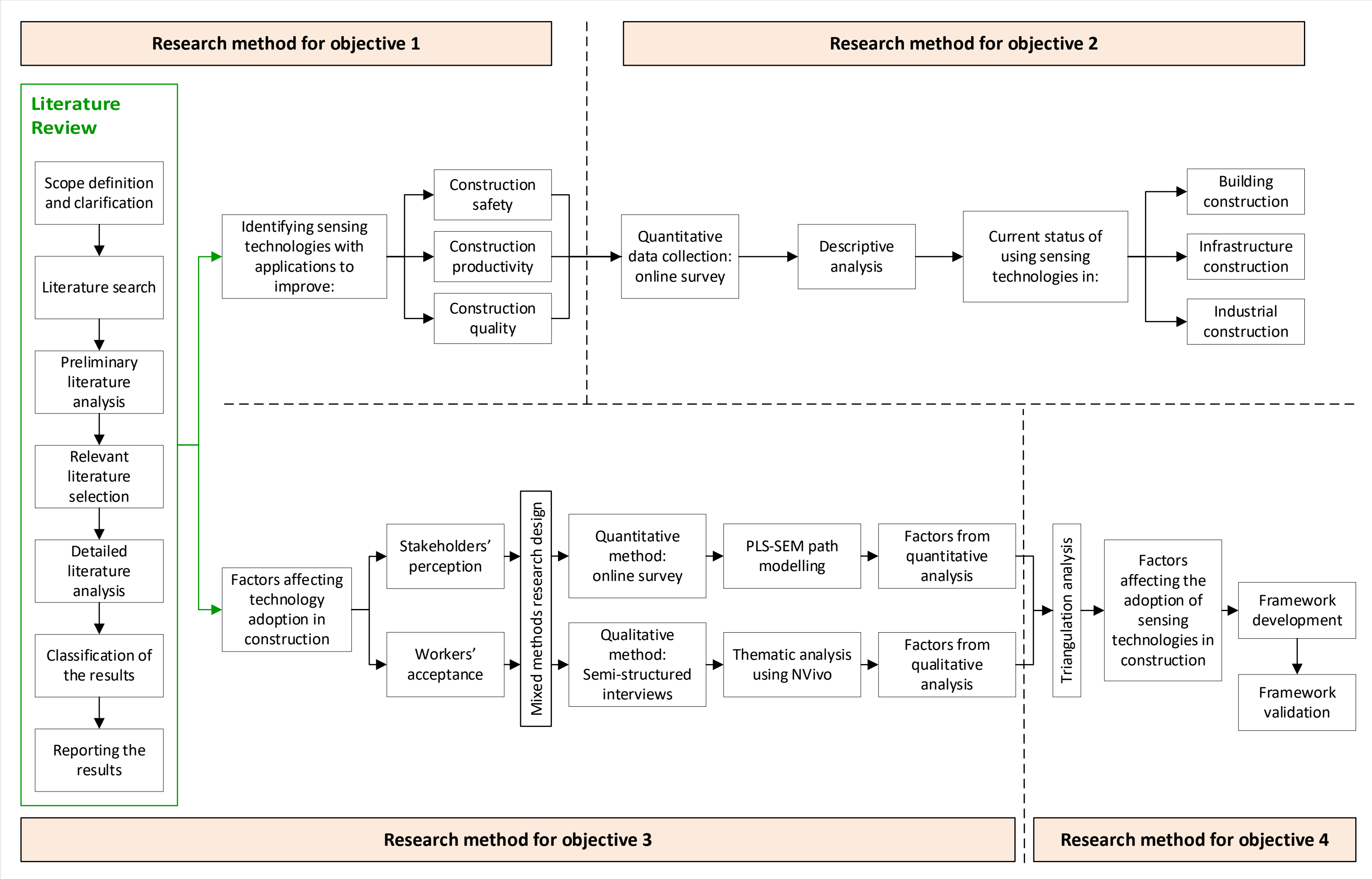
3.4 Research Methods

In general, methodological choices for research are either qualitative, quantitative or mixed method which is the combination of the two (Saunders, Lewis and Thornhill 2015).

In this research, a subjectivism philosophy entails using qualitative research methods (Darlaston-Jones 2007) through affecting research epistemology by placing the researcher in the position of interacting with what is researched (Klenke 2016). In other words, subjective meanings constitute dominant knowledge in this present research which leads to the adoption of a qualitative research method. Besides, qualitative methodology is suitable for pursuing a deeper understanding of that which is not accessible through quantification (Darlaston-Jones 2007). Qualitative methodology emphasises relativistic ontology (subjectivism) that approves multiple realities socially constructed by individuals from their contextual interpretation (Klenke 2016). The nature of this research is mostly qualitative as the researcher is eager to find out what qualities and which characteristics in different types of sensing technologies play important roles in sensing technology adoption. However, objective 2 of this research demands the current use of sensing technologies be quantified. Moreover, the researcher believes that objective 3 can also benefit from employing a quantitative approach to examine whether factors affecting the adoption of other types of emerging technologies in construction are also significant in sensing technology adoption and can be applied in the governance framework of this research. Consequently, there is a need for a quantitative method of data collection and analysis.

As a result, a mixed methods research design will be employed to both examine the significance of identified factors reported in the literature and also explore for extended factors and further value-adding information latent in construction professionals' perceptions and experience. Figure 3.2 depicts the design of the research methods for each objective of this current research, followed by an explanation of the methods for each of the four objectives.

Figure 3.2 *Research methods design*



3.4.1 Research methods for objective 1

Objective 1 is to obtain an understanding of the existence and applicability of sensing technologies with potential benefits during construction. This objective is deemed to be achievable through an extensive literature review investigating and discussing the applications and benefits of different types of sensing technologies in construction. Therefore, the method of research for this objective is literature research and reporting the results.

A seven-step research method was designed to fully address objective 1. Five steps were for the literature review on applicable sensing technologies in the construction industry and the two final steps were classifying types of identified sensing technologies and then reporting the results. In this regard, the most common sensing technologies in the context of construction research were identified, along with their applications in construction and then classified according to the aspect of construction performance meant to be improved by using those technologies. The research method for objective 1 is illustrated in Figure 3.2, comprising seven steps of a literature review to identify the most appropriate sensing technologies to improve construction safety, productivity, and quality.

The following steps were taken for the literature review.

Step 1: Scope definition and clarification

As the first step prior to literature search, the scope of research should be clarified. According to the scope, only those types of sensing technologies used for continuous monitoring and are capable of improving either safety, productivity or quality in construction performance have been considered for the review. This means devices and technologies for testing purposes were excluded. Likewise, greater emphasis was on state-of-the-art and innovative sensors rather than sensors that have been fully established and implemented during construction processes, such as some types of environmental sensors that are prerequisites to construction activities.

Step 2: Literature search

The majority of the literature was identified in databases such as “ScienceDirect”, “ProQuest”, “Emerald”, “ICONDA” and “Ei Village”.

Keywords were used to look for relevant resources. The most-used keywords were: "sensing technology", "sensor", "construction site", "construction performance", "construction safety", "construction productivity", "construction quality", "technology adoption", etc. In addition, citations in identified articles were followed to find additional suitable literature.

Step 3: Preliminary literature analysis

Identified articles in step 2 were analysed by going through their titles, abstracts and conclusions to determine whether they fitted the scope of this research. A time span or limit for publication of the articles focused on the most recent research, which was the period from 2009 to 2020, with a few exceptions before 2009. More reasons for the selection of the time span are given in section 2.2.2.

Step 4: Relevant literature selection

After the preliminary analysis, those articles which satisfied all required criteria were selected for detailed analysis in the next step.

Step 5: Detailed literature analysis

Relevant resources were analysed in more detail to extract the relevant information for the background of the current research. In this step, relevant literature on sensing technologies were classified based on the aspect of construction performance that they intend to improve (safety, productivity or quality).

Step 6: Classification of the findings

Findings from the analysis of relevant articles in the previous step were further classified according to the type of sensors they studied and their applications in the construction industry. More details were extracted from each article on a case-by-case basis.

Step 7: Reporting the results

The last step to completely address objective 1 was to report the findings of the literature review. The general structure of the report was based on the aspect of the construction performance and area of construction management that the identified sensing technology would improve.

More details on the research methods for objective 1 are provided in section 2.2.

3.4.2 Research methods for objective 2

Objective 2 is to identify in-use sensing technologies during the construction phase in actual projects and estimate their prevalence in order to compare against findings from the literature. This objective is addressed through a quantitative method which provides a quantified report on the popularity and rates of sensing technology usage to improve construction safety, productivity or quality in real construction projects. In order to do so, an online survey to collect the data was followed by a descriptive analysis of the data to find out how frequently each type of sensing technology is used by the construction industry.

The online survey was distributed among construction professional in different sectors of the construction industry, being building construction, infrastructure construction and industrial construction. Distribution channels for administering the online survey were emails, LinkedIn messages and snowball sampling.

The online survey was designed in two parts to accommodate for data collection for both objectives 2 and 3. The first part of the online survey made inquiries about the frequencies of using selected types of sensing technologies. For this purpose, the most frequently noted sensing technologies in the literature were included in the online survey. The rate of using such technologies were questioned to find out the prevalence of their adoption by construction companies in real projects to improve construction safety, productivity, or quality. Descriptive analysis was used to understand the current status of sensing technologies in construction and to report on the extent to which the construction industry adopted different types of sensing technologies. The descriptive analysis resulted in graphical and quantified results of the actual implementation of selected sensing technologies in the construction industry. More details on the research methods for objective 4 is presented in Chapter 4.

3.4.3 Research methods for objective 3

Objective 3 is to understand construction stakeholders' perceptions of sensing technologies, affiliated effectiveness, benefits and barriers, as well as major factors influencing sensing technology adoption in construction. Achieving this objective is critical for achieving objective 4 and the research aim. Hence, after an extensive literature review on factors affecting the adoption of sensing technologies in construction, concurrent quantitative and qualitative methods were employed to benefit from the advantages of both and to reduce possible disadvantages of each (Fellows and Liu 2015).

The first stage of objective 3 was a literature review on the factors that influence technology adoption in construction, with a focus on digital technologies. The literature review for objective 3 followed the seven steps specified in section 3.4.1 except that the time span was more flexible and allowed for a wider period of publication. The literature search involved key words such as: “technology adoption”, “construction stakeholders’ perceptions and acceptance”, etc. The literature search also referred to the citations of relevant articles. Not only the adoption of sensing technologies was considered for the literature search, but also the adoption of similar innovative technologies (mostly IT-based) since the literature on sensing technology adoption was scarce. Relevant literature was classified according to identified factors affecting the adoption of sensing technology. A mixed methods research design with concurrent quantitative and qualitative approaches was used for data collection. Each set of data was analysed accordingly. The factors identified in the literature review were used as a basis for both quantitative and qualitative data collection. These factors are reported in Chapter 2.

Quantitative data collection for objective 3 took place through the same online survey as used for objective 2. The second part of the online survey explored the importance of factors identified in the literature that might affect the adoption of sensing technologies in construction to partially cover objective 3. Then, a proper Structural Equation Modelling (SEM) technique was employed to find out whether or not the factors reported in the literature for the adoption of other types of technologies significantly affect sensing technology adoption. More details on survey design, distribution, responses, and methods for the quantitative data analysis are provided in Chapter 4.

Qualitative data collection took place through face-to-face semi-structured interviews with highly experienced construction professionals. An interview questionnaire was designed and improved after a pilot study to accommodate for a comprehensive set of questions on sensing technology adoption in construction. The interview invitations for recruiting participants were distributed through emails and LinkedIn messages to construction professionals. Snowball sampling was also used for the distribution of interview invitations. It is worth mentioning that although the distribution channels for qualitative data collection were the same as the quantitative data collection, there were two separate samples of data for each of the methods. Eligible interviewees were carefully selected from those who responded to the interview invitations and officially invited to participate in the research. Upon the participant’s voluntary consent to be audio recorded, a face-to-face interview was conducted at their preferred time and venue. As the sample size for a qualitative approach was dependant on data saturation qualitative data analysis was done after each interview and concurrently during data collection. Interview recordings were carefully transcribed and extensively analysed to extract value-adding information. Factors extracted from qualitative analysis were classified in relevant categories to cover different aspects of sensing technology adoption in construction. More details on methods for qualitative data collection and analysis are provided in Chapter 5.

3.4.4 Research methods for objective 4

Objective 4 was to develop a framework that would assist the process of new sensing technology adoption into construction practices, highlighting motivations and the barriers and concerns that need to be addressed to achieve wider adoption. This objective, which is in line with the ultimate aim of this research, was achieved through triangulation analysis of both quantitative and qualitative results and applicable findings from the literature. The triangulated results then informed the governance framework to address the fourth objective and meet the aim of the research.

Triangulation analysis involved combining the results reported in Chapter 4 and Chapter 5 and cross-checked to eliminate repetitions, and were then compared to the literature for additional factors. Accordingly, the framework was developed by firstly generating a structure to represent the process of technology adoption and allowing for various aspects and groupings to determine the factors. Factors from each of the quantitative and qualitative sets of results were allocated to appropriate sections of the framework and, finally, a comparison with the literature accommodated any possible missing factors needed to make the framework more comprehensive.

The governance framework that resulted from the triangulation analysis was validated by industry professionals who responded to an evaluation and validation survey. The data from the online survey improved the framework and validated it. More details on research methods for objective 4 are explained in Chapter 6.

3.5 Justification of the Methods

Aside from the literature review and associated research methods, this present research has used both qualitative and quantitative data collection methods to address objectives 2 and 3. This section presents a justification for the selected methods of data collection.

Each of the quantitative and qualitative data collection methods are commonly used in construction management research and are known to have comprehensive outcomes (Fellows and Liu 2015). Surveys as a quantitative data collection method and interviews as a qualitative data collection method have been widely used for previous research in different areas of construction management, four examples of which are briefly discussed as follows.

– Construction productivity

Construction productivity, an essential component of construction management, has benefited from qualitative-quantitative methods of research. Examples are the use of structured interviews with project managers, contractors and consultants along with questionnaire surveys to examine factors constraining on-site construction productivity (Durdyev and Ismail 2016) and to identify best practices regarding material management in urban confined construction sites (Spillane and Oyedele 2017). Individual interviews with project managers were also used to study the effectiveness of human resource management framework on construction sites (Othman et al. 2018) and to learn about issues in material management in confined construction sites (Spillane et al. 2011).

– Waste management

Waste management is an area in which qualitative research in the form of questionnaire surveys and follow up interviews were used as data collection methods to develop a BIM-aided construction waste minimisation framework (Liu et al. 2015). Likewise, Tam, Le, and Wang (2017) investigated solid waste management in India partly through interview discussions. Ding et al. (2018) conducted semi-structured interviews to identify important factors of construction waste reduction at the design and construction stages.

– Risk management

Ahmad, Thaheem, and Maqsoom (2018) collected data in the form of an international survey from BIM practitioners with hands-on experience and open-ended interviews with five international construction experts to examine the influence of BIM on risk management and to observe the transformation of risk from a traditional management system into a BIM-based system. Lam and Siwingwa (2017) used combined qualitative-quantitative exploratory methods to identify risk factors that caused project cost overruns during a construction phase. The qualitative approach included interviews with five construction practitioners. Feng and Wu (2015) also used semi-structured interviews to validate the findings from their quantitative surveys regarding risk compensation behaviours in construction workers.

- Technology adoption

Mixed qualitative-quantitative research methods have previously been used to explore the adoption of emerging technologies in construction such as in identifying construction stakeholders' attitudes towards the new technologies and associated decision making processes (Sepasgozar and Davis 2018), and for exploring barriers to BIM adoption (Hong et al. 2016).

Surveys are a powerful and common means of quantitative data collection to understand stakeholders' views of various aspects of construction management. Examples are:

- perceived benefits of digitalisation in different stages of construction (Aghimien et al. 2018)
- benefits and challenges of ICT adoption (Akinbile and Oni 2016; Usman and Said 2012)
- barriers to ADC technology adoption (Sardroud 2014)
- construction employees' willingness to use wearable sensors (Jacobs et al. 2019; Schall, Sesek and Cavuoto 2018)
- adoption of 3D printing in construction (Wu et al. 2018)
- attitudes towards IoT-based work safety on construction sites (Häikiö et al. 2020).

Qualitative research methods were also used in the form of semi-structured interviews to research different areas of technology adoption in construction such as discovering the barriers to BIM adoption (Alreshidi, Mourshed and Rezgui 2017; Kraazt, Sanchez and Hampson 2014), identifying ways of improving the project decision making mechanism and hence maximising the satisfaction of involved stakeholders in major infrastructure and construction projects (Li, Ng and Skitmore 2013) and construction equipment technology adoption (Sepasgozar and Loosemore 2017).

3.6 Summary

The chapter acknowledged philosophical standpoints that governed the selection of appropriate research methods for this investigation. Ontological, epistemological and axiological aspects of research philosophy were discussed and declared as were the reasoning approach and methodological choices. The methods used for each of the four objectives were also outlined and explained.

The methods used in the conduct of this present research were literature review, quantitative data collection using an online survey, descriptive analysis of quantitative data on the current status of sensing technologies in construction, SEM path modelling of quantitative data on factors affecting the adoption of sensing technologies, qualitative data collection using semi-structured interviews, qualitative analysis of interview transcriptions, and a triangulation analysis of the results from all of the noted methods.

Finally, this chapter reviewed previous studies in the field of construction management research with similar approaches to data collection and analysis, to justify the selection of methods used in this present research.

Chapter Four

4

Quantitative Data Collection and Analysis

4.1 Introduction

This chapter is dedicated to addressing objective 2 fully and objective 3 partially. In order to understand the current status of sensing technologies in real construction projects and to address the second objective of this research, quantitative data was collected and analysed to investigate which types of sensing technologies have already been implemented during the construction phase in different sectors of the construction industry, and to what extent they have been implemented. Quantitative data was collected regarding the frequencies of using selected sensing technologies in real construction projects and analysed for prevalence.

On the other hand, many factors affecting the adoption of different types of digital technologies in construction have been identified and reported in the literature as mentioned in Chapter 2. Although some factors were reported within the context of sensing technologies or ADC technologies in construction (Sardroud 2014; Schall, Sesek and Cavuoto 2018; Jacobs et al. 2019), the majority of these factors were reported to affect other categories of technology adoption in construction such as IT, ICT, ADC, BIM, etc. The present research was interested to examine whether such factors also play an important role in sensing technology adoption in construction according to stakeholders' perceptions of the importance of such factors. This partially covers objective 3 and is feasible through collecting quantitative data on the importance of identified factors and then, with Structural Equation Modelling (SEM), investigating the significance of each factor and examining those factors that influence others. SEM returns solid results of significant factors affecting the adoption of sensing technologies in construction to partially cover the third objective of this research.

Quantitative data collection was pursued in the form of an anonymous online survey asking for demographic information, and the current status and factors affecting adoption of sensing technologies in construction.

4.2 Design of the Survey

Design of the online survey had two goals. The first was to investigate the frequencies of the use of various types of sensing technologies during the construction phase in different sectors of the construction industry: building construction, infrastructure construction and industrial construction. This part makes inquiries about how frequently-selected sensing technologies are being used to improve different aspects of construction performance, which are safety, productivity or quality. The second goal, the foremost aim of the data collection, was to examine the importance of different factors affecting the adoption of sensing technologies in construction.

The first part of the survey was to gather demographic information about the respondents. It included questions from the respondents about the sector of the construction industry they work in, size of their company (regarding number of staff and annual turnover), years of experience they have in construction and their position within the company.

The second part of the survey was about current implementation status of sensing technologies in construction. The most frequently noted sensing technologies in the context of construction management research were identified through the literature. Respondent were asked if their company was using the technology to improve construction safety, productivity or quality. The frequencies of responses were gathered on a five-point Likert scale based on the "seven, plus or minus two" principle (Miller 1956). The five-point Likert scale asked how frequently each of the selected technologies was in use: "a daily basis", "frequently from time to time", "only occasionally", "very rarely" and "not at all".

The third and fourth parts of the survey gathered information about factors affecting the adoption of sensing technologies in construction, including the barriers preventing or limiting sensing technology implementation in construction, as well as motivations towards adopting innovative sensing technologies by construction stakeholders. These two sections also used a five-point Likert scale to gather responses. The likelihood of barriers and importance of motivations regarding the adoption of new sensing technologies were scaled as follows: "extremely likely/important", "very likely/important", "moderately likely/important", "slightly likely/important" and "not likely/important at all". Appendix A is the text of the online survey.

4.2.1 Pilot study to develop and review the questionnaire survey

As a result of the literature review, eight different types of sensing technologies and 21 factors influencing the adoption of digital technologies in construction were selected and reviewed by three industry professionals for a pilot test. The pilot study consisted of individual discussions with one construction manager with 10 years of experience, one site manager with 7 years of experience and one project manager with 5 years of experience in construction. All three construction professionals were familiar with and experienced in using some types of sensing technologies in construction. The list of sensing technologies, as well as the list of factors categorised into six groups, were presented to each of the construction professionals. The list of sensing technologies was easily approved by all three professionals.

Relevance and suitability of factors to sensing technology adoption and to their related factor groupings were discussed and improved through the pilot test. The list of factors contained both barriers and motivations associated with sensing technology adoption in construction. All 21 factors were approved by the construction professionals, however the sequence and classification were slightly modified. Three additional factors were suggested by the participants and added to the list of factors to make it more comprehensive. The three newly-added factors were: "safety issues" as a barrier, and "trial sessions" and "proof of effectiveness in similar projects" as motivations. The complete list of 24 factors their classification in six factor groupings is presented in Table 4.1.

4.3 Quantitative Data Collection

4.3.1 Target population of respondents

Potential respondents for the quantitative data collection were construction stakeholders and practitioners who widely represented the construction industry with specific roles as construction managers/directors, project managers/directors, technical managers/directors, and technology managers/directors. Other construction professionals experienced with sensing technologies could also respond to the survey and specify their position as "other". The key eligibility to participate in the research was to have considerable experience in construction, and some knowledge and experience in using sensing technologies. The profile of respondents is presented in section 4.3.3.

4.3.2 Distribution and responses

The larger the sample size for data collection the fewer are sampling errors likely but on a decreasing rate (Taherdoost 2017). However, if variables are reliable and the model is not too complex, smaller sample sizes could be enough (Iacobucci 2010). To support this claim, many construction management researchers have used relatively small sample sizes (Molwus, Erdogan and Ogunlana 2017). Examples include: BIM adoption influential factors in small and medium-sized construction companies (Hong et al. 2016) with a sample of 120 participants and 40 responses, VIM benefits and challenges in construction industry (Didehvar et al. 2018) with a sample size of 32 respondents, Impact of IT adoption on the quality of construction projects in Jordan (Sweis et al. 2015) with a sample of 90 participants and factors affecting the implementation of web-based systems on construction project management (Doloi 2014) with 77 respondents.

Different distribution channels were used to circulate information about the online survey. Major channels were direct emails and LinkedIn messages plus snowball sampling to ensure that the invitees worked in relevant areas and held eligible positions. Also, invitation emails were sent to construction companies introducing the research and requesting them to share an anonymous link to the online survey with key stakeholders and decision makers within the company. LinkedIn has been identified as a useful channel for distributing surveys as it is a professional social network that lets researchers connect with relevant professionals. Hence, for this present study construction professionals from different sectors of the construction industry were contacted through LinkedIn and invited to take part in the survey.

The online survey tool used for generating and distributing the online questionnaire survey did not force answers to all questions, with the result that some responses returned missing data, however, the researcher believed that not using a forced-answer approach effectively reduced the number of respondents who might have abandoned the survey.

A total of 261 invitations were sent to construction professionals all over Australia by emailing them directly or through their companies, plus LinkedIn messages. Snowball sampling was also used to recruit key construction stakeholders and practitioners for the survey.

All respondents whose responses contained missing data that equalled or was greater than 15% were excluded from the analysis (Hair Jr et al. 2016). In total 88 questionnaires were completed, of which six were excluded from data analysis due to missing data, resulting in 82 completed questionnaires for analysis. Mean value replacement where used for those responses having less than 5% missing data (Hair 2017). Since the online survey was anonymous, there was no way to estimate how many respondents from each of the distribution channels (emails, LinkedIn or snowballing) completed the survey. Considering the sample size of 261, a response rate of 31.5% was achieved with 82 complete questionnaires which was acceptable in construction studies (Sardroud 2014).

4.3.3 Profile of respondents

From 82 survey respondents from all over Australia, 30 (37%) were from the building sector, 34 (41%) from the infrastructure sector and 18 (22%) from the industrial construction sector. The majority of respondents held top managerial positions. Among the respondents were 21 construction managers or construction directors (26%), 27 project managers or directors (33%) and 19 technical managers or directors (23%). The rest of the respondents were holding other positions such as technology managers or directors, project engineers, surveyors, site engineers and business developers. Most of the respondents had more than 10 years of experience in construction (35% more than 20 years, and 36% between 10–20 years of experience), and were from companies with an annual turnover of more than $1 million (in Australian currency). The sizes of the companies of the respondents were almost normally distributed between companies with under 50 employees (17%), companies with 50–100 employees (20%), companies with 100–200 employees (18%), companies with 200–500 employees (21%) and companies with more than 500 employees (24%). Figure 4.1 – Figure 4.5 show the profile of respondents.

Figure 4.1 *Responses from different construction sectors*

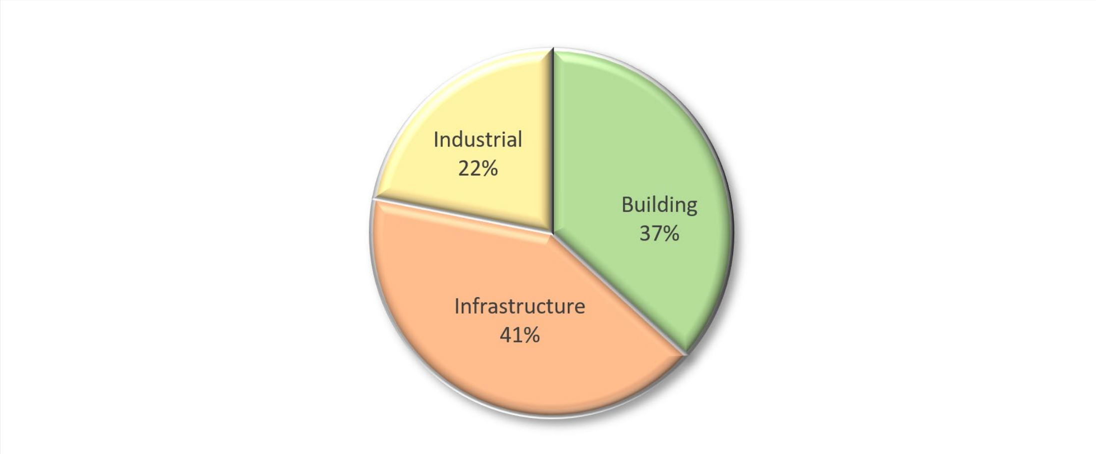


Figure 4.2 *Respondents' positions*

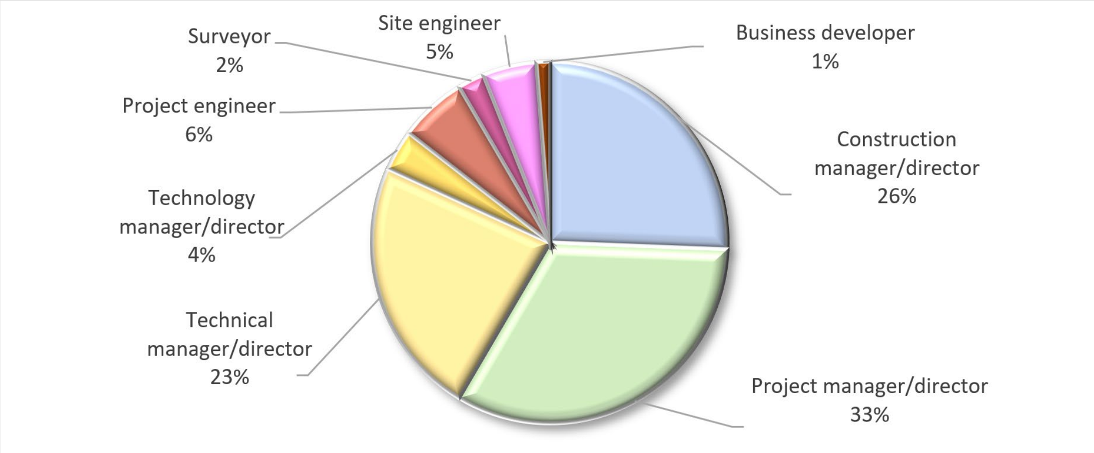


Figure 4.3 *Respondents' experience in construction*

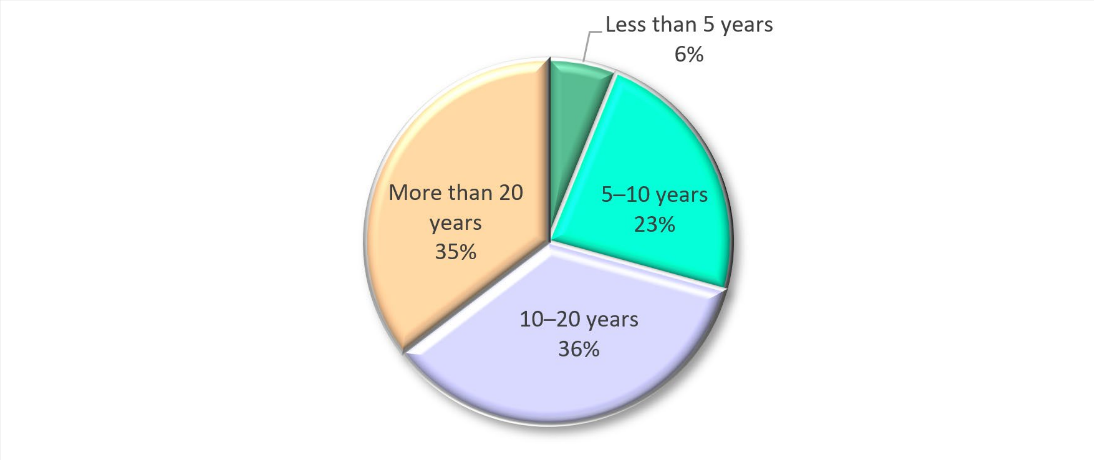


Figure 4.4 *Size of the companies regarding their number of staff*

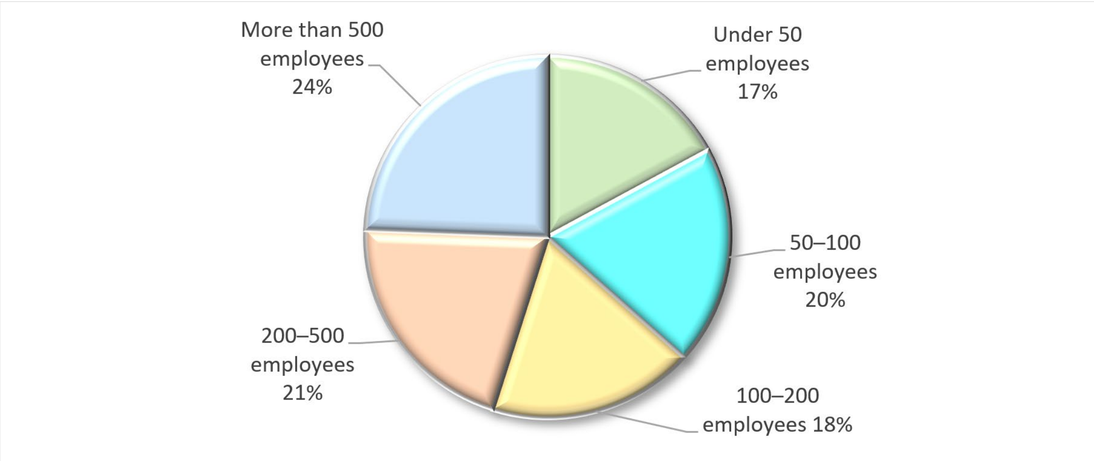
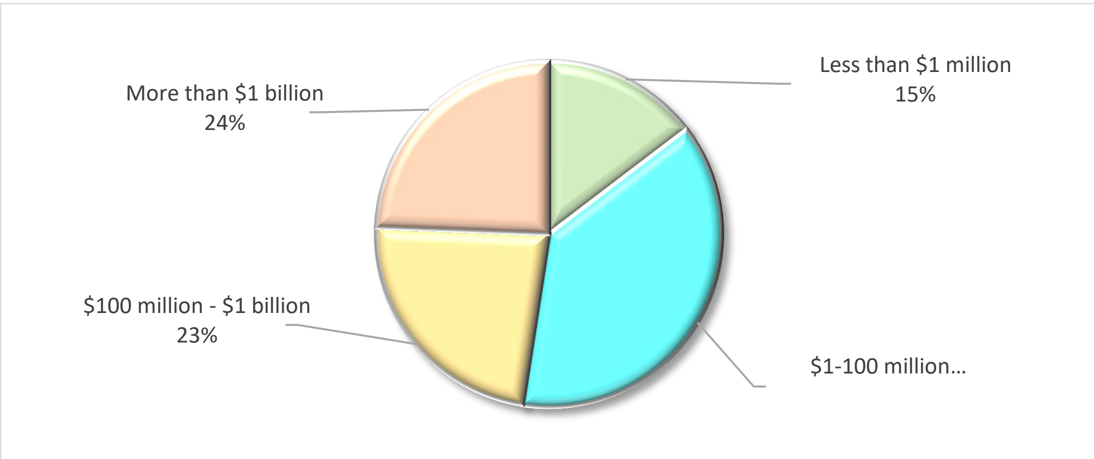


Figure 4.5 *Size of the companies regarding their annual turnover*



4.4 Current Status of Sensing Technologies in Construction

As mentioned earlier, the current status of sensing technology implementation in Australian construction projects has been investigated through the online survey in order to address objective 2. Eight of the most frequently noted sensing technologies identified throughout the literature were nominated to be investigated in this part of the survey. These technologies were: GPS, RFID, UWB, FOS, pressure sensing, temperature sensing, visual sensing, and 3D scanning. Selected technologies were either the ones that were widely noted in the literature (GPS, RFID, UWB) but not widely accepted or even learned by industry professionals, or the ones that serve in certain construction operations such as pressure or temperature sensors. State-of-the-art technologies in construction research (such as wearable sensors) were excluded from the questionnaire, although the respondents could specify any additional type of sensors that they use which were not already included in the survey. Enquires were made to investigate how frequently the selected technologies are being used in construction projects, as a demonstration of their current status in Australian construction industry.

The frequencies of using the noted sensing technologies were recorded on a five-point Likert scale based on the "seven, plus or minus two" principle (Miller 1956). The five points were: "not using at all", "using very rarely", "using only occasionally", "using frequently from time to time", and "using on a daily basis". The respondents were asked to report the frequencies by which each of the noted sensing technologies were used during the construction projects in their company.

A descriptive analysis of the collected data on the current status of selected sensing technologies in order to improve construction performance produced results for each sector of the construction industry: building construction, infrastructure construction and industrial construction. Sections 4.4.1 to 4.4.8 illustrate and discuss the current status of GPS, RFID, UWB, FOS, pressure sensing, temperature sensing, visual sensing and 3D scanning.

The descriptive analysis of the current status of sensing technologies in construction confirmed literature findings of the slow adoption of such technologies (Stewart, Mohamed and Marosszeky 2004; Love and Irani 2004). A cross-sector comparison shows that GPS and visual sensing, the two most widely implemented sensing technologies in construction (see Sections 4.4.1 and 4.4.7), are still not adopted by many construction companies, especially in the building and infrastructure sectors. UWB was identified as the least frequently adopted sensing technology between all the eight selected technologies in all the three sectors.

4.4.1 Current status of GPS implementation in construction

GPS was recognised as one of the most frequently used sensing technologies in all three sectors of construction compared to other types of technologies under study. However, building construction still lagged behind the other two sectors in the uptake of GPS. Of the 30 respondents from the building sector and 34 respondents from the infrastructure sector, 16% and 9%, respectively, said they did not use GPS in their construction projects. All respondents from the industrial sector acknowledged they used GPS in their construction projects at least to some degree. Figure 4.6 – Figure 4.8 show the current status of GPS use in construction.

Figure 4.6 *Current status of using GPS in building construction*

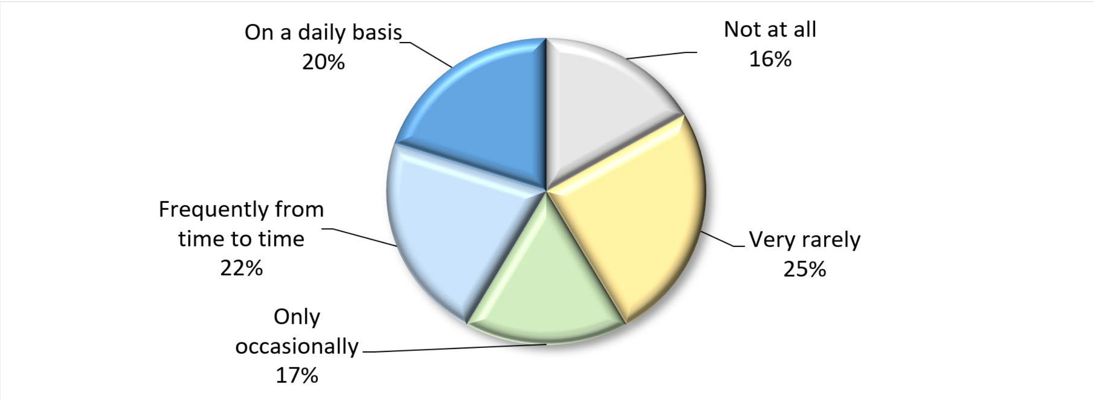


Figure 4.7 *Current status of using GPS in infrastructure construction*

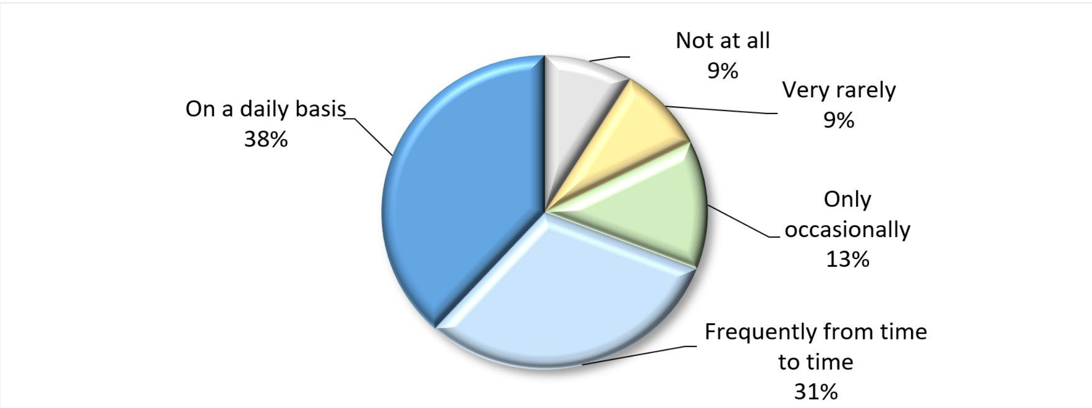
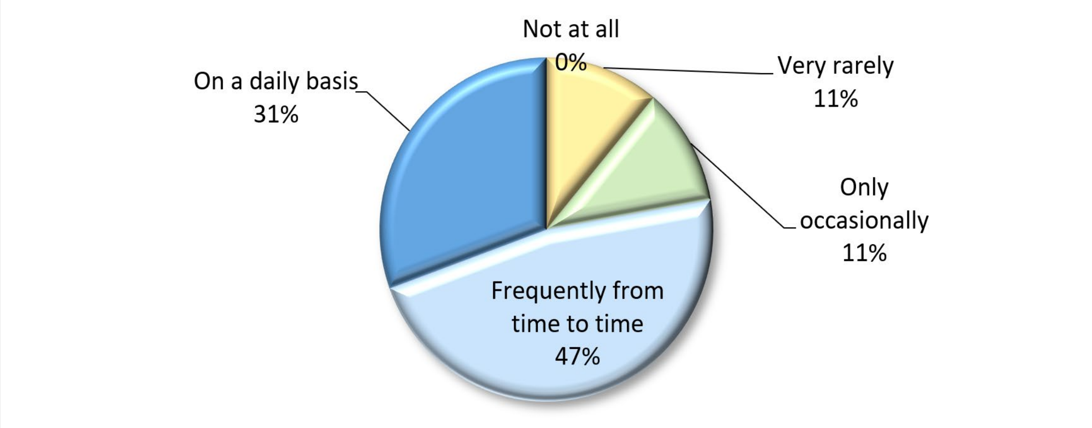


Figure 4.8 *Current status of using GPS in industrial construction*



4.4.2 Current status of RFID implementation in construction

The use of RFID technology is far less prevalent in the construction industry compared to GPS. Of respondents working in the building sector 75% were not using RFID in their projects at all, whereas about half of the respondents from the other two sectors were using RFID at some level. Figure 4.9 – Figure 4.11 show the frequency of RFID technology use in each of the three sectors of the construction industry.

Figure 4.9 *Current status of using RFID in building construction*

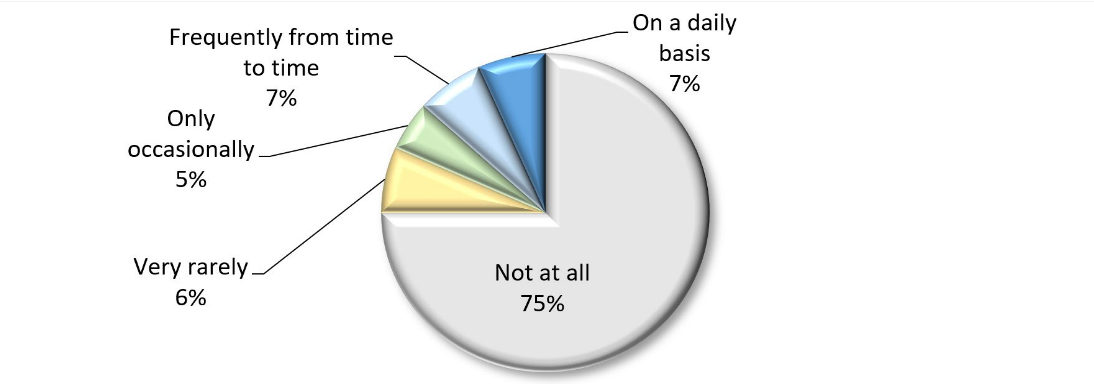


Figure 4.10 *Current status of using RFID in infrastructure construction*

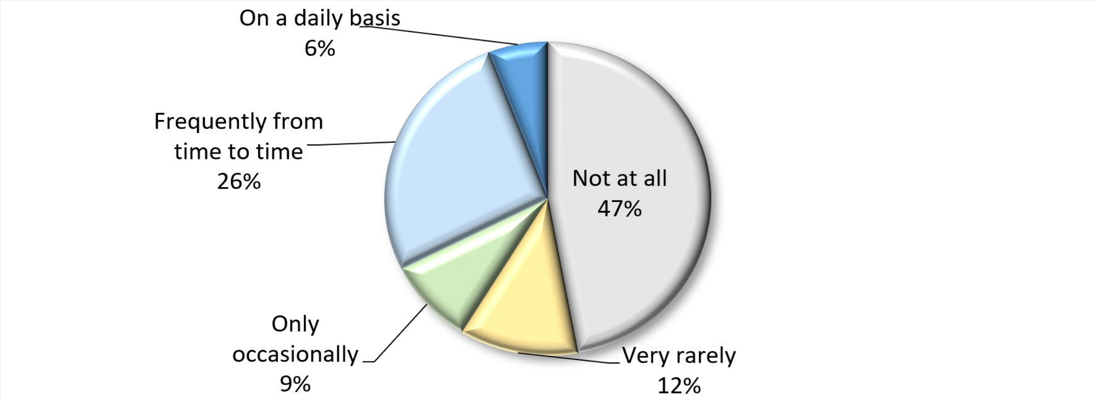
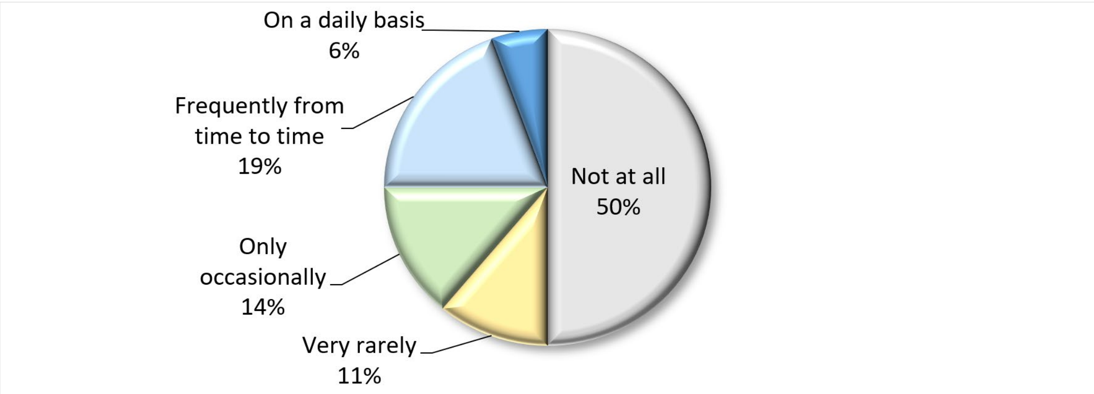


Figure 4.11 *Current status of using RFID in industrial construction*



4.4.3 Current status of UWB implementation in construction

UWB technology was found to have the lowest level of implementation among all eight technologies. Of respondents from the building sector 82% were not using UWB at all and usage in the infrastructure sector was not far behind (77%). Of respondents from industrial construction, 58% were not using UWB at all and only 3% used it on a daily basis. Figure 4.12 – Figure 4.14 depict the current status of UWB implementation in each sector.

Figure 4.12 *Current status of using UWB in building construction*

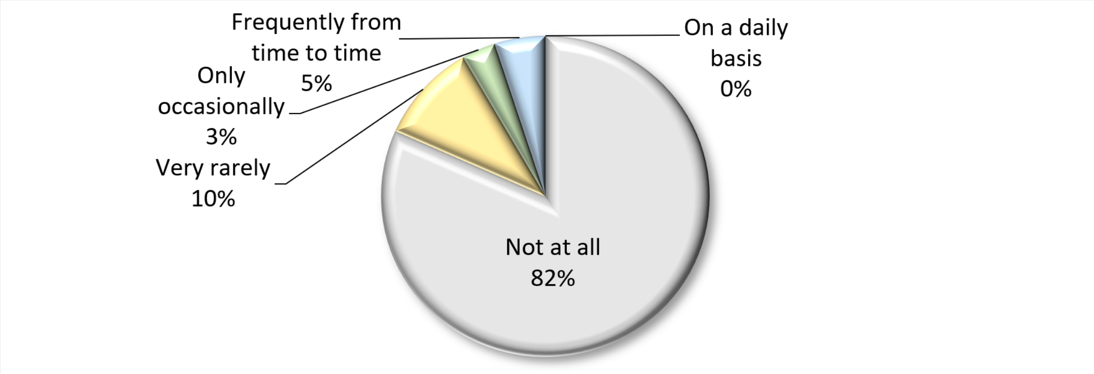


Figure 4.13 *Current status of using UWB in infrastructure construction*

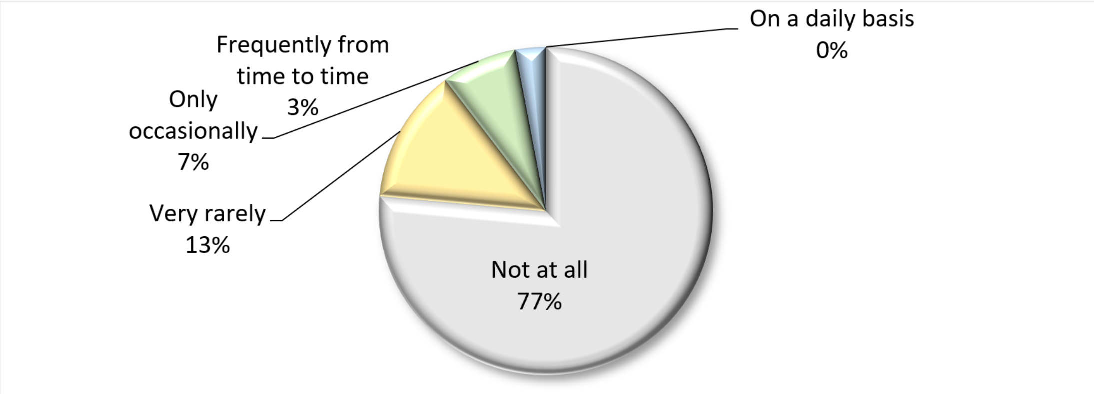
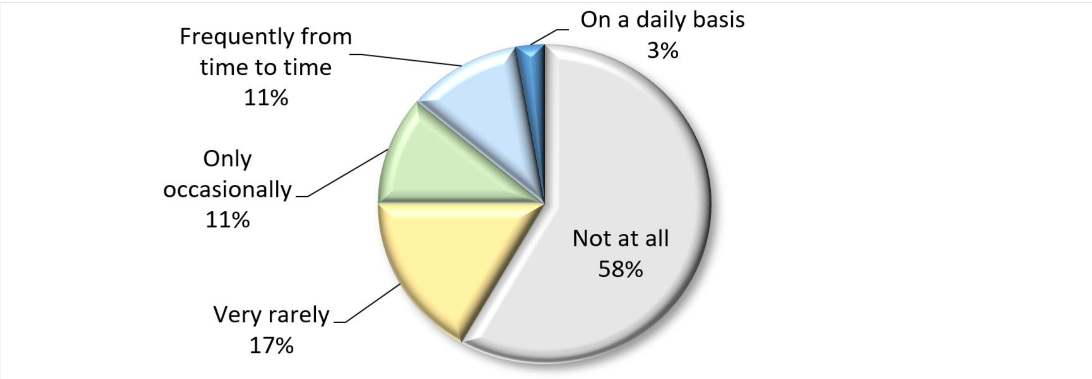


Figure 4.14 *Current status of using UWB in industrial construction*



4.4.4 Current status of FOS implementation in construction

The descriptive analysis of the current status of FOS implementation has revealed that this technology is more prevalent in industrial construction than in building or infrastructure construction. Figure 4.15 – Figure 4.17 show that 72% and 69% of projects in the building and infrastructure sectors respectively were not involved in any form of FOS implementation, whereas 70% of industrial construction projects include some types of FOS at least at some level.

Figure 4.15 *Current status of using FOS in building construction*

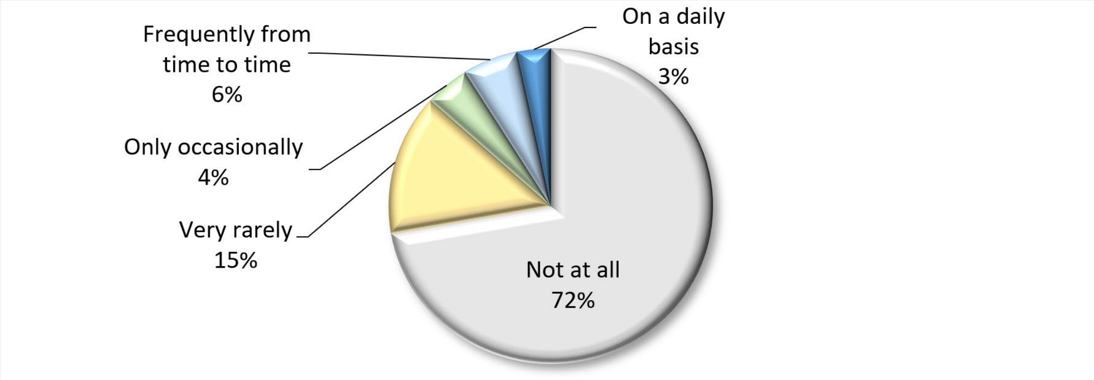


Figure 4.16 *Current status of using FOS in infrastructure construction*

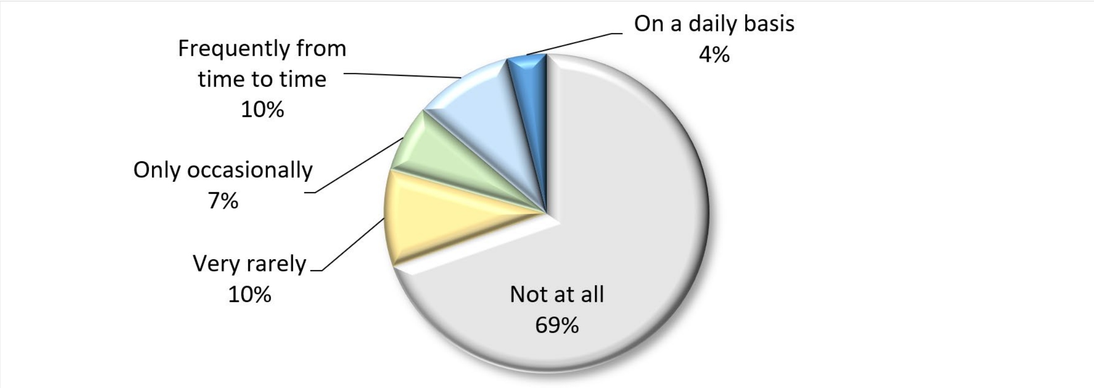
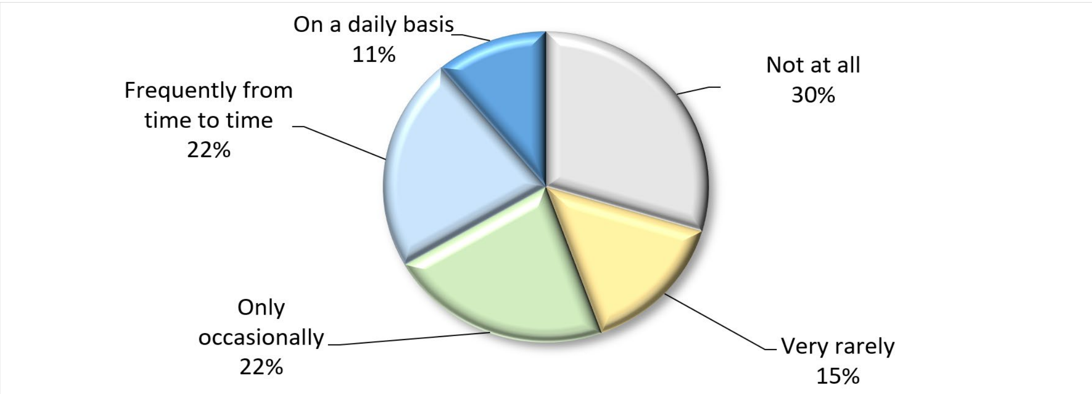


Figure 4.17 *Current status of using FOS in industrial construction*



4.4.5 Current status of pressure sensing implementation in construction

Pressure sensing is more prevalent in the industrial construction compared to the building and infrastructure construction. From the industrial sector respondents, 11% acknowledged they use pressure sensors in their construction projects on a daily basis, whereas only 3% of respondents from the infrastructure sector used them on the same level and none of the building construction respondents used pressure sensors. Figure 4.18 –

Figure 4.20 illustrate the current status of pressure sensing across the three sectors of the construction industry.

Figure 4.18 *Current status of using pressure sensing in building construction*

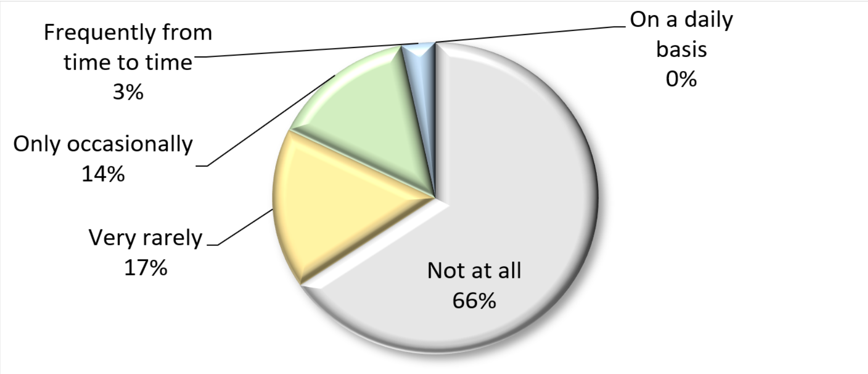


Figure 4.19 *Current status of using pressure sensing in infrastructure construction*

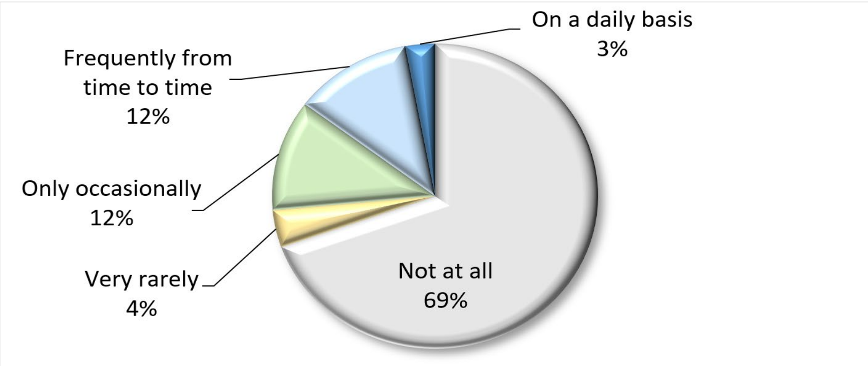
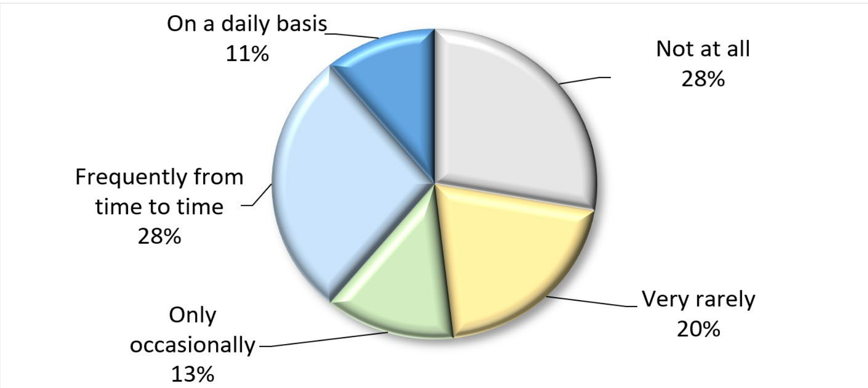


Figure 4.20 *Current status of using pressure sensing in industrial construction*



4.4.6 Current status of temperature sensing implementation in construction

Temperature sensing, sometimes a requirement for environmental monitoring, has a higher level of implementation in all three sectors of construction. More than half of the respondents in each sector were using it in their construction projects at some level. Figure

4.21 – Figure 4.23 illustrate the current status of the use of temperature sensors during construction projects across the three sectors.

Figure 4.21 *Current status of using temperature sensing in building construction*

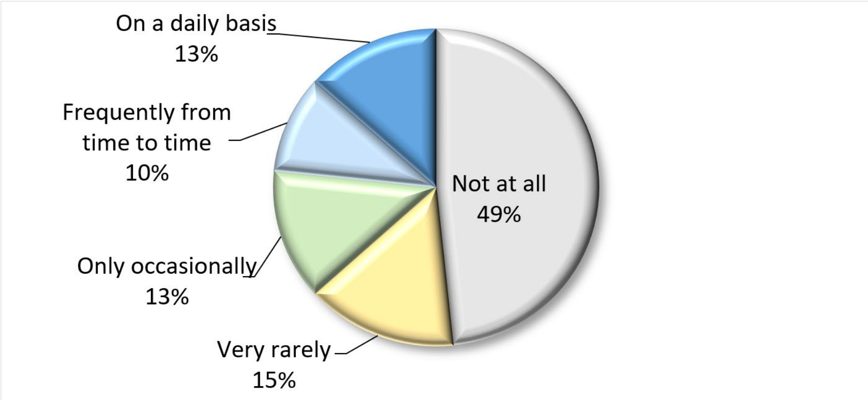


Figure 4.22 *Current status of using temperature sensing in infrastructure construction*

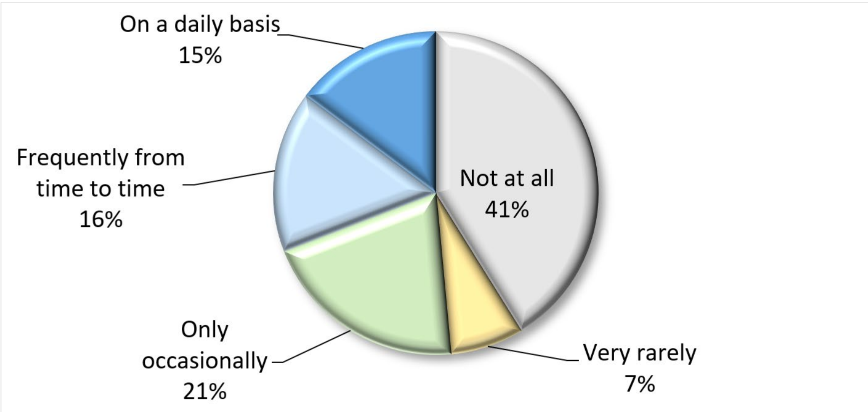
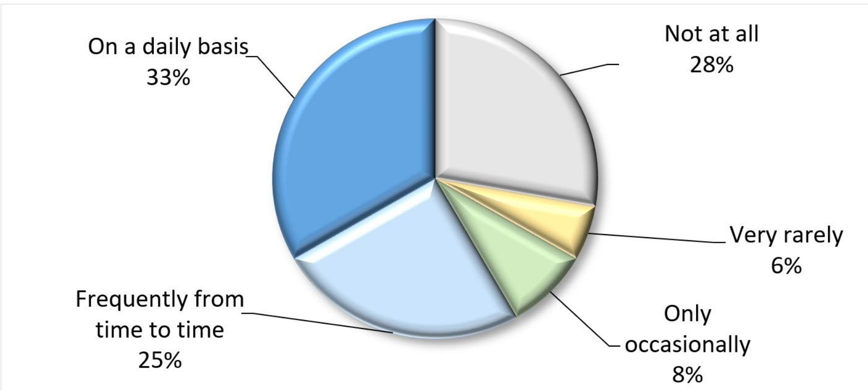


Figure 4.23 *Current status of using temperature sensing in industrial construction*



4.4.7 Current status of visual sensing in construction

Visual sensing (including visual recordings) is one of the most popular types of sensing technologies in construction. From the building construction respondents, 75%

acknowledged they used some types of visual sensing at some level. For infrastructure and industrial construction projects, the rates rose to 83% and 86% respectively. The current status of visual sensing across three sectors of the construction industry is presented in Figure 4.24 – Figure 4.26.

Figure 4.24 *Current status of using visual sensing in building construction*

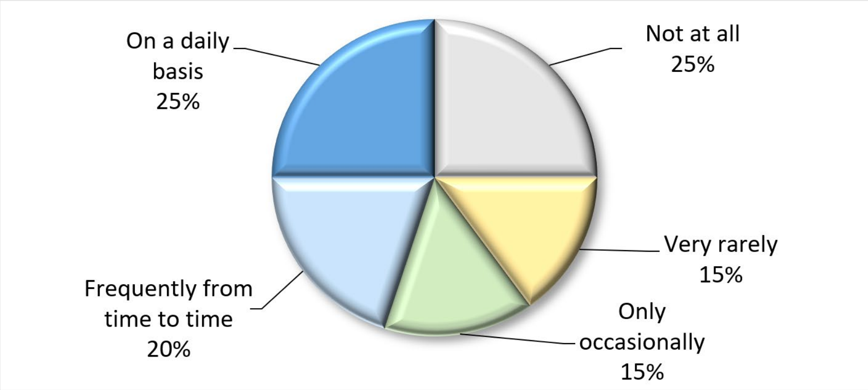


Figure 4.25 *Current status of using visual sensing in infrastructure construction*

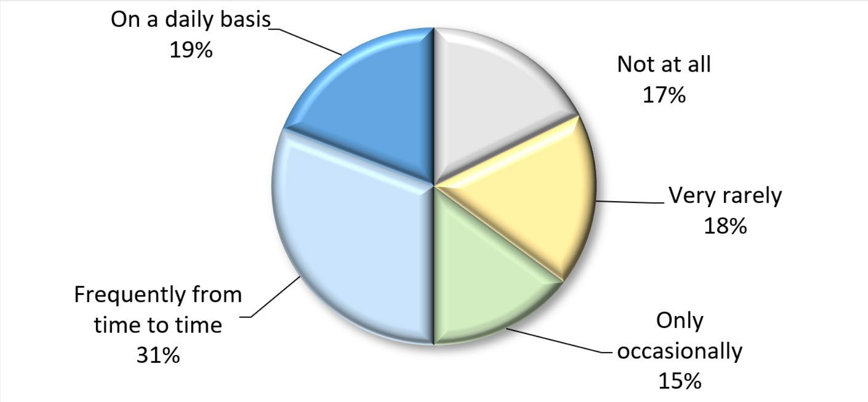
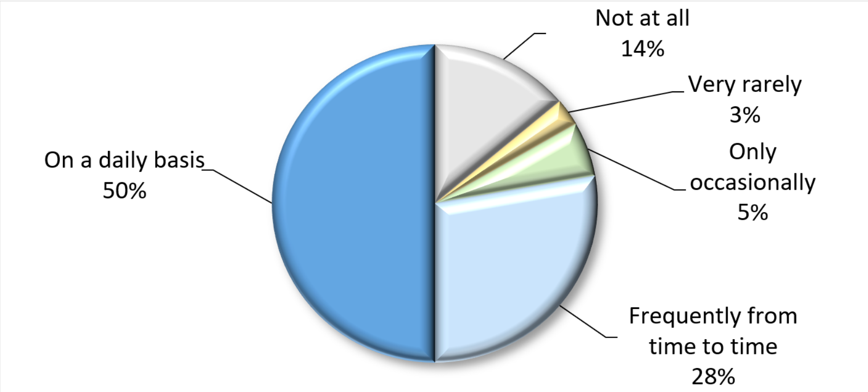


Figure 4.26 *Current status of using visual sensing in industrial construction*



4.4.8 Current status of 3D scanning in construction

3D scanning (or laser scanning) is considered as a type of visual recording in this study although its current status was investigated separately because of increasing attention towards its benefits in the construction industry. 3D scanning was implemented more in industrial construction projects rather than in building or infrastructure. Of industrial construction projects 22% used 3D scanners on a daily basis while in the case of building and infrastructure construction only 3% was on a daily basis. Only 14% of respondents from industrial construction were not using 3D scanners while 44% and 49% of respondents from building and infrastructure construction respectively said that they did not use 3D scanners in their projects at all. Figure 4.27 – Figure 4.29 show the current status of 3D scanning technology across the three sectors of the construction industry.

Figure 4.27 *Current status of using 3D scanning in building construction*

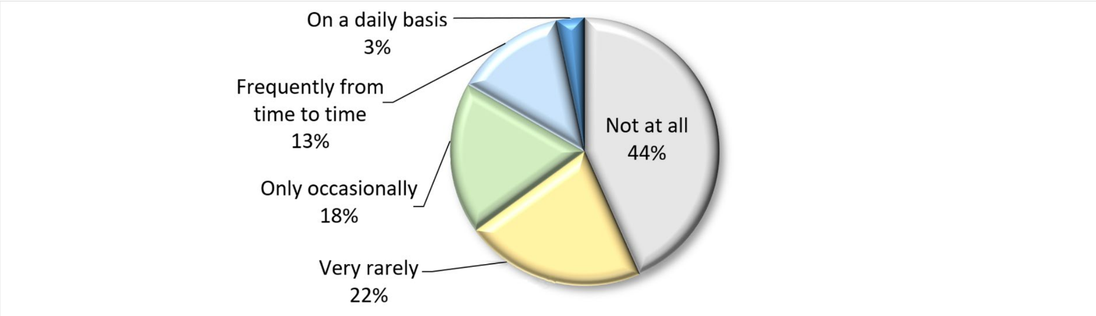


Figure 4.28 *Current status of using 3D scanning in infrastructure construction*

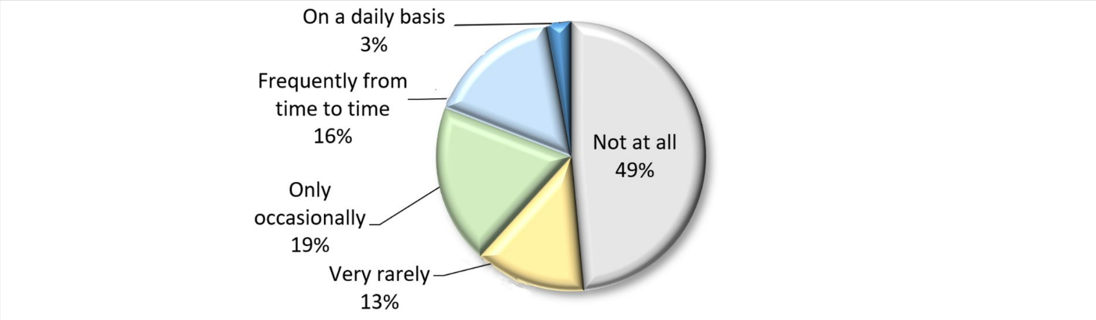
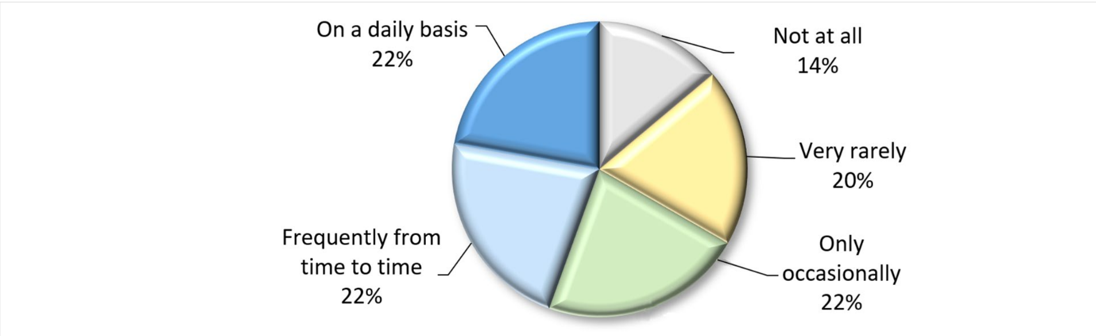


Figure 4.29 *Current status of using 3D scanning in industrial construction*



4.5 Factors Affecting the Adoption of Sensing Technologies in Construction

The main goal of quantitative data collection was to find out whether the factors identified in the literature that influence the adoption of different types of digital technologies also apply in the case of sensing technology adoption. In this regard, construction professionals rated the importance of 24 factors in an online survey and SEM was employed to examine if those factors significantly affect the adoption of sensing technologies in construction. The 24 selected factors were categorised into six factor groupings according to their meanings and relevant literature review for better understanding and ease of data analysis (Table 4.1).

Obviously, the six factor groupings were not independent but had influences on each other. Therefore, a primary conceptual framework was developed to depict the interrelationships between these groups of factors as shown in Figure 4.30.

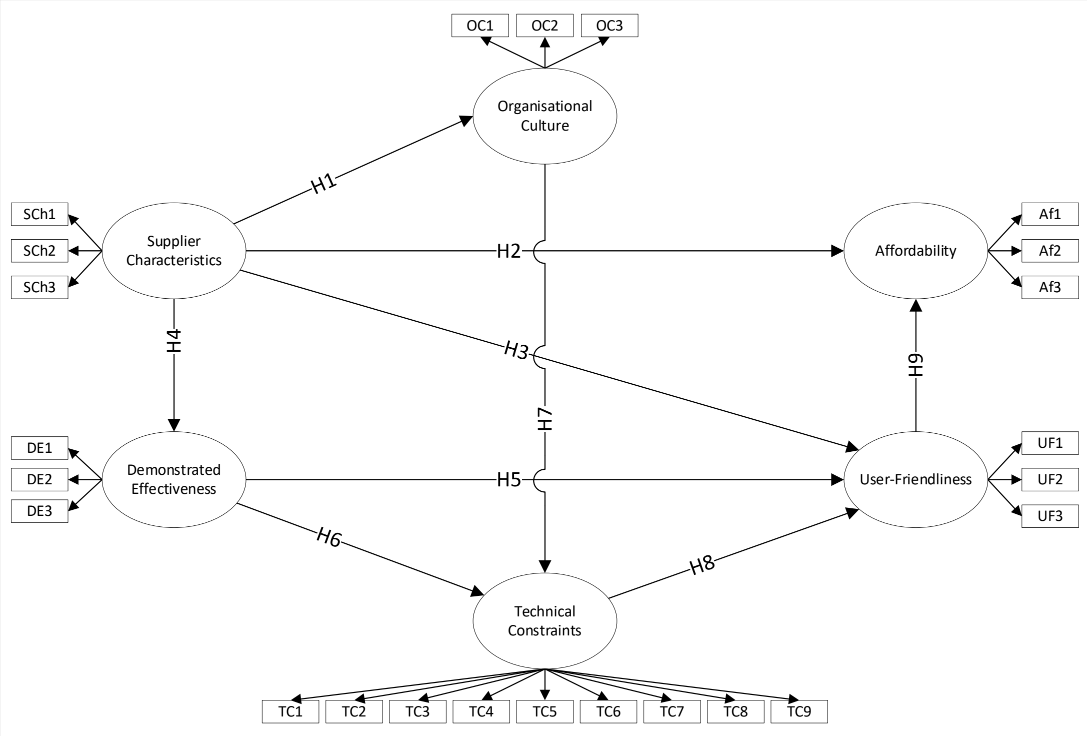
It was hypothesised that some of these factor groupings had significant influences on some others. The interrelationships between these factor groupings represented the research hypotheses in this chapter and were presented as paths in the conceptual framework. The nine assumed hypotheses are as follows.

- Hypothesis 1: Supplier characteristics positively affect organisational culture.
- Hypothesis 2: Supplier characteristics positively affect affordability.
- Hypothesis 3: Supplier characteristics positively affect user friendliness.
- Hypothesis 4: Supplier characteristics positively affect demonstrated effectiveness.
- Hypothesis 5: Demonstrated effectiveness positively affect user friendliness.
- Hypothesis 6: Demonstrated effectiveness positively affect technical constraints.
- Hypothesis 7: Organisational culture positively affect technical constraints.
- Hypothesis 8: Technical constraints positively affect user friendliness.
- Hypothesis 9: User friendliness positively affect affordability.

Table 4.1 *Factors affecting the adoption of sensing technologies in construction*

Grouping / Indicators	Factors
Affordability	
Af1	Implementation cost
Af2	Maintenance cost
Af3	Skill acquisition cost
Demonstrated Effectiveness	
DE1	Proof of effectiveness from other industry parties
DE2	Proof of effectiveness on trial sessions
DE3	Proof of effectiveness in similar projects
Organisational Culture	
OC1	Organisational support and approval
OC2	Acceptance between employees
OC3	Ethical concerns and privacy of employees
Supplier Characteristics	
SCh1	Reputation of the supplier
SCh2	Quality training support from the supplier
SCh3	Quality support from the supplier during maintenance
Technical Constraints	
TC1	Safety issues
TC2	Accuracy issues
TC3	Effectiveness issues
TC4	Not adaptable with IT infrastructure
TC5	Hard to get quality technical support
TC6	Hard to manage and analyse too much collected data
TC7	Hard to get quality training
TC8	Hard to maintain
TC9	Power supply issues
User-friendliness	
UF1	Easiness of handling data
UF2	Simplicity of use
UF3	Compatibility with current systems and activities

Figure 4.30 *The primary conceptual framework*



The significance of the 24 factors in the conceptual framework and hypothesised interrelationships between factor groupings were examined with SEM procedures. The structural model was evaluated to include only significant factors and revised to determine whether any changes were necessary to achieve a sophisticated model that reflected as many significant factors and paths as possible.

4.5.1 Structural Equation Modelling

Structural Equation Modelling (SEM) indirectly measures unobservable variables through their theoretical relationship with observed variables or indicators. SEM is not a single statistical technique but a family of statistical techniques providing researchers with the ability to test multivariate models (Weston and Gore 2006; Kline 2015) and can be very effective in non-experimental research (Byrne 2013; Kline 2015). SEM is capable of both factor analysis (in the measurement model) and path analysis (in the structural model) where it can assist researchers to determine the interrelationship between a number of dependent and independent variables, as well as to examine hypothesised relationships between constructs (Weston and Gore 2006; Molwus, Erdogan and Ogunlana 2017). Path modelling is used to graphically represent variable relationships and research hypotheses (Hair Jr et al. 2016).

According to the literature, there is a growing trend in the application of SEM in construction management research (Molwus, Erdogan and Ogunlana 2013) where there usually are latent variables that cannot be directly observed but are related to measurable and observable variables. Such an explicit distinction between observed variables (collected data) and latent variables (hypothetical constructs that cannot be directly observed) is a key feature of SEM, which enables the researcher to identify such relationships between latent and observed variables (Byrne 2013; Kline 2015).

Latent variables in SEM are either exogenous or endogenous. Exogenous latent variables are the same as independent variables by which the changes in their values are external and thus not explained by the model. Endogenous latent variables, however, are the same as dependent variables which are either directly or indirectly influenced by exogenous variables. Any fluctuation in the values of endogenous variables is internal to the model and hence is explained within the model (Byrne 2013).

There are two types of SEM: Covariance-Based Structural Equation Modelling (CB-SEM) and Partial Least Squares Structural Equation Modelling (PLS-SEM) or PLS path modelling which relies on variances to determine an optimum solution (Hair Jr et al. 2016). PLS-SEM was used in this research for the structural modelling of the conceptual framework.

4.5.1.1 Partial Least Square Structural Equation Modelling

PLS-SEM, a variance-based algorithm originally developed in the 1980s by Herman Wold (Hair Jr et al. 2016) and more recently modified by other researchers (Bentler and Huang 2014; Dijkstra 2014; Dijkstra and Henseler 2015). Although the CB-SEM was predominant (Hair et al. 2019) PLS-SEM is increasingly used in social science studies. There are three basic components usually visible in a PLS-SEM model (Hair Jr et al. 2016).

- Constructs or latent variables are unobservable variables that the researcher intends to measure indirectly through observable variables. Constructs are shown in a path model with circles or ovals. Two types of constructs are defined within a PLS model: exogenous latent variables which explain and predict other constructs, and endogenous latent variables which are predicted by other latent variables.
- Indicators or manifest variables are observed variables that have been directly measured and contain raw data. Indicators are shown with rectangles in a PLS model.

- Relationships between constructs and relationships between a construct and its own indicators are shown with single-headed arrows in a PLS-SEM path model. Single-headed arrows between constructs of a PLS-SEM model represent research hypotheses and are considered predictive relationships between the constructs within the model.

A PLS-SEM path model consists of two parts: a structural model and a measurement model. The structural model or the inner model represents the relationships between constructs within the model whereas the measurement model or the outer model represent the relationships between the constructs and their indicators. The first step in defining a PLS-SEM model is to specify both structural and measurement models. Then, quantitative data is assigned to the model and a PLS-SEM algorithm estimates all unknown elements within the model. When all the path coefficients are estimated, both the measurement model and structural models should be evaluated before analysing and interpreting the results (Hair 2017).

PLS-SEM is capable of handling two types of measurement models, reflective and formative. Reflective indicators represent the reflections or manifestations of their related construct and are therefore affected by the construct. Reflective indicators of a construct are highly correlated with one another and so are interchangeable, meaning that a single item can be left out of the model without affecting the meaning of the construct. Moreover, if the latent construct changes for any reason, all reflective indicators will go through the same change simultaneously. Formative indicators on the other hand, are assumed to be the causal indicators establishing the construct. Formative indicators are not interchangeable, since every one represents one aspect of the construct and their linear combination form the construct. Therefore, it is not possible to eliminate a formative indicator because it will alter the construct (Hair Jr et al. 2016; Lowry and Gaskin 2014).

4.5.1.2 Justification of data analysis method

PLS-SEM is suitable for exploratory research where there is no well-established theory, and the researcher is trying to develop a theory (Lowry and Gaskin 2014; Hair et al. 2019). This supports the inductive approach of this research, as stated in section 3.3. In addition, it is widely used in construction management research to test multivariate conceptual frameworks (Wu et al. 2018; Feng et al. 2017; Liu, Zhao and Li 2017; Doloi 2014).

PLS-SEM has been selected for structural path analysis in this research over CB-SEM due to its ability to handle non-normal data and small samples sizes. Table 4.2 shows occasional non-normalities in the distribution of data and makes the model more appropriate for a PLS-SEM model rather than the CB-SEM model.

A relative small sample size (82 respondents) is another reason to choose PLS-SEM because sample size requirements in PLS-SEM are lower compared to CB-SEM, since PLS-SEM deals better with measurement error (Hair 2017). In PLS-SEM the rule of thumb method to roughly estimate the minimum sample size (Hair 2017; Lowry and Gaskin 2014) is that the sample size used in a PLS-SEM model should be at least equal to the larger of:

- either 10 times the largest number of formative indicators measuring a single construct, or
- 10 times the largest number of structural paths directed at a construct within the model.

According to those requirements for the sample size of a PLS-SEM model and considering the proposed model, the maximum number of paths directed at a latent variable in the PLS-SEM model is three (see Figure 4.30), which means the minimum acceptable sample size would be 30, which is less than 82, the sample size used for this research. It is worth mentioning that the sample size is from a restricted population, hence it qualifies as an acceptable sample size for PLS-SEM (Rigdon 2016).

Table 4.2 *Normality tests for data distribution*

Grouping / Indicator	Skewness	Kurtosis	Kolmogorov-Smirnov		Shapiro-Wilk	
			Statistic	Significance	Statistic	Significance
Affordability						
Af1	-0.140	-0.908	0.226	0.000	0.835	0.000
Af2	-0.741	0.352	0.275	0.000	0.817	0.000
Af3	-0.089	-0.680	0.222	0.000	0.876	0.000
Demonstrated Effectiveness						
DE1	-1.007	1.361	0.319	0.000	0.824	0.000
DE2	-1.232	1.625	0.260	0.000	0.786	0.000
DE3	-1.363	1.464	0.312	0.000	0.747	0.000
Organisational Culture						
OC1	-0.404	-0.418	0.207	0.000	0.892	0.000
OC2	-0.311	-0.588	0.222	0.000	0.899	0.000
OC3	0.219	-1.045	0.174	0.000	0.892	0.000
Supplier Characteristics						
SCh1	-0.806	-0.138	0.251	0.000	0.837	0.000
SCh2	-1.013	1.211	0.277	0.000	0.818	0.000
SCh3	-1.034	1.135	0.245	0.000	0.813	0.000
Technical Constraints						
TC3	-0.207	-0.634	0.179	0.000	0.914	0.000
TC4	-0.144	-1.030	0.234	0.000	0.881	0.000
TC5	0.390	-0.529	0.217	0.000	0.904	0.000
TC6	-0.150	-0.857	0.174	0.000	0.912	0.000
TC7	-0.120	-0.398	0.229	0.000	0.900	0.000
TC8	-0.225	-0.719	0.186	0.000	0.910	0.000
User-friendliness						
UF1	-0.861	-0.119	0.288	0.000	0.790	0.000
UF2	-1.141	0.831	0.306	0.000	0.757	0.000
UF3	-0.771	-0.310	0.255	0.000	0.812	0.000

4.5.1.3 Model specification

In order to look at the significance of the factors and examine research hypotheses, PLS-SEM was employed to model the conceptual framework and test whether hypothesised paths were supported.

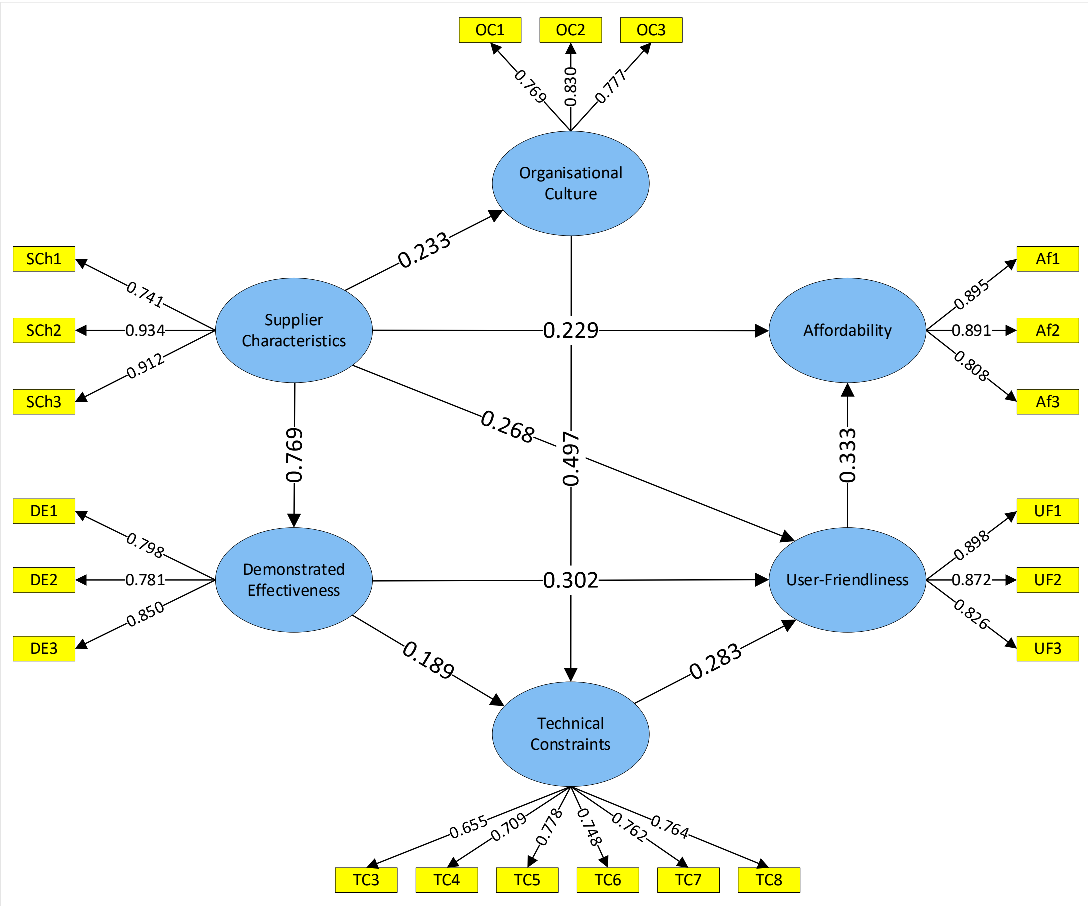
The first step was to specify the structural model or the path model. The path model consists of the structural model or the inner model (which illustrates the relationships between latent variables or constructs) and the measurement model or the outer model (which represents the relationships between latent variables and their corresponding indicators) (Hair 2017). The structural model was initially defined as shown in Figure 4.30 comprising of nine paths describing the relationships between the six constructs. Then the measurement model was specified to represent how the constructs are measured through the 24 independent variables. All of the six constructs were measured reflectively as the independent variables represents the manifestation of the relevant construct (Hair 2017).

After a few trials of model estimation, three of the indicators (TC1, TC2 and TC9) were removed from the model since they were either not significant in the PLS model or were negatively affecting the reliability of the model. Consequently, the final PLS-SEM model had 21 indicators with the same number of constructs and paths. Figure 4.31 shows the final model with the factor loadings and path coefficients (to be discussed later in more detail).

There are various software programs for running PLS-SEM algorithms however SmartPLS 3 is reported to be the most comprehensive software for the purpose of this research (Hair 2017). Data from the 82 responses was assigned to the PLS model and then PLS algorithm calculations followed by bootstrapping techniques were used to estimate the loadings for the measurement model and the structural model. Since there was occasional non-normality in the distribution of input data, bias-corrected and accelerated bootstrapping calculation methods were used in SmartPLS to avoid as much skewness as possible (Hair et al. 2019).

Assessment of a PLS model began with measurement model evaluation to check the reliability and validity of the construct measures. If the measurement model was reliable and valid, it was ready for structural model evaluation (Hair 2017).

Figure 4.31 *PLS model with factor loadings and path coefficients*



4.5.1.4 Measurement model evaluation

There are measures to ensure the data is reliable before proceeding to the interpretation of results and assessing the hypotheses. Hence, it was necessary to evaluate the measurement model to assess the reliability and validity of input data.

Data reliability

Looking into the reliability of collected data was a prerequisite to data analysis indicating the degree to which the data set was free from random measurement errors (Kline 2010). Internal consistency reliability of data has been reported in similar research through Cronbach's alpha coefficient. The recommended threshold for Cronbach's alpha is reported to be 0.7 (Nunnally 1978). Cronbach's alpha coefficient for all 21 indicators was 0.89, showing high internal reliability. The Cronbach's alpha coefficient calculated for each of the six constructs had slightly lower values but are still above the minimum requirement of 0.7 (see Table 4.3).

Internal consistency reliability can also be measured through Composite Reliability which considers outer loadings of the indicators (Hair 2017). All the values for composite reliability for all the six constructs were between 0.8 and 0.9 which are considered satisfactory (see Table 4.3).

Table 4.3 *Model reliability measures*

Grouping / Indicator	Loading	t-value	Cronbach's Alpha*	Composite Reliability
Affordability				
Af1	0.895	22.800		
Af2	0.891	24.769	0.835	0.899
Af3	0.808	13.407		
Demonstrated Effectiveness				
DE1	0.798	10.396		
DE2	0.781	9.785	0.737	0.851
DE3	0.850	26.390		
Organisational Culture				
OC1	0.769	9.323		
OC2	0.830	20.339	0.704	0.835
OC3	0.777	12.591		
Supplier Characteristics				
SCh1	0.741	11.070		
SCh2	0.934	53.766	0.828	0.899
SCh3	0.912	30.989		
Technical Constraints				
TC1	0.655	9.984		
TC2	0.709	8.755		
TC3	0.778	14.950		
TC4	0.748	12.578		
TC5	0.762	12.309	0.832	0.877
TC6	0.764	12.315		
TC7	0.655	9.984		
TC8	0.709	8.755		
TC9	0.778	14.950		
User-friendliness				
UF1	0.898	34.936		
UF2	0.872	21.068	0.833	0.900
UF3	0.826	20.412		

Indicator reliability of the measurement model is evaluated by the factor loadings. All the factor loadings are statistically significant at 95% confidence level as all values are above the threshold of 0.5 (Hair 2017). Also, the t-values for a two-tailed test resulting from the bootstrapping technique are all above 2.57, showing acceptable indicator reliability at a level of confidence equal to 99%.

Data validity

Two types of measures should be considered for the validity of data. One is convergent validity and the other is discriminant validity.

Convergent validity indicates how well an indicator correlates positively with other indicators of the same construct and is assessed through the average variance extracted (AVE). All AVE values for all the six constructs are above the minimum requirement of 0.5 (Hair 2017). Table 4.4 shows AVE values for convergent validity of the measurement model.

Discriminant validity shows the extent of distinction between various constructs within the model, indicating that every construct is unique and different from other constructs (Hair 2017). The first approach to assess discriminant validity of a PLS model is to check the cross loadings and ensure that each factor has the highest loading on its respective construct. Table 4.5 shows the factor loadings and cross loadings of indicators. Values in bold are the loadings on their relevant constructs and are higher than any of the cross loadings on other constructs. The second approach to assess discriminant validity compares the square root of the AVE values with the correlations between other constructs. In this approach the square root of AVE for each construct should be higher than the correlation between the same construct and any other construct. This approach is demonstrated through Fornell-Larcker Criterion in SmartPLS. Table 4.6 shows Fornell-Larcker Criterion and the square roots of AVE compared to other correlations.

Table 4.4 *AVE values for convergent validity*

Grouping / Indicator	AVE
Affordability	
Af1	
Af2	0.749
Af3	
Demonstrated Effectiveness	
DE1	
DE2	0.656
DE3	
Organisational Culture	
OC1	
OC2	0.628
OC3	
Supplier Characteristics	
SCh1	
SCh2	0.751
SCh3	
Technical Constraints	
TC3	
TC4	
TC5	0.544
TC6	
TC7	
TC8	
User-friendliness	
UF1	
UF2	0.750
UF3	

Table 4.5 *Cross-loadings of the measurement model*

	Construct					
Indicator	**Affordability**	**Demonstrated Effectiveness**	**Organisational Culture**	**Supplier Characteristics**	**Technical Constraints**	**User-Friendliness**
Af1	**0.895**	0.382	0.137	0.325	0.232	0.369
Af2	**0.891**	0.451	0.154	0.427	0.272	0.500
Af3	**0.808**	0.247	0.113	0.327	0.088	0.305
DE1	0.362	**0.798**	0.112	0.596	0.184	0.475
DE2	0.348	**0.781**	0.142	0.653	0.172	0.424
DE3	0.334	**0.850**	0.126	0.621	0.288	0.522
OC1	0.239	0.313	**0.769**	0.277	0.404	0.353
OC2	0.093	0.082	**0.830**	0.153	0.454	0.244
OC3	0.026	-0.053	**0.777**	0.110	0.389	0.226
SCh1	0.267	0.523	0.324	**0.741**	0.390	0.509
SCh2	0.434	0.765	0.119	**0.934**	0.234	0.527
SCh3	0.384	0.692	0.187	**0.912**	0.170	0.493
TC3	0.168	0.241	0.403	0.174	**0.655**	0.359
TC4	0.326	0.200	0.309	0.214	**0.709**	0.302
TC5	0.108	0.119	0.373	0.213	**0.778**	0.214
TC6	0.122	0.227	0.419	0.297	**0.748**	0.337
TC7	0.146	0.149	0.377	0.170	**0.762**	0.273
TC8	0.192	0.214	0.418	0.231	**0.764**	0.414
UF1	0.435	0.556	0.344	0.558	0.383	**0.898**
UF2	0.397	0.406	0.330	0.368	0.460	**0.872**
UF3	0.375	0.543	0.236	0.576	0.314	**0.826**

Table 4.6 *Fornell-Larcker Criterion for discriminant validity*

	Construct					
Grouping	**Affordability**	**Demonstrated Effectiveness**	**Organisational Culture**	**Supplier Characteristics**	**Technical Constraints**	**User-Friendliness**
Affordability	**0.866**					
Demonstrated Effectiveness	0.429	**0.810**				
Organisational Culture	0.158	0.156	**0.792**			
Supplier Characteristics	0.423	0.769	0.233	**0.866**		
Technical Constraints	0.240	0.267	0.527	0.297	**0.737**	
User-Friendliness	0.466	0.585	0.350	0.587	0.442	**0.866**

Meeting all the above-noted criteria, the measurement model was deemed to be reliable and valid for further analysis. The next step was to evaluate the structural model.

4.5.1.5 Structural model evaluation

PLS-SEM structural model evaluation looks at the model-predictive capabilities and relationships between the constructs. The first step in structural model evaluation was to check for collinearity issues and then to check the structural model path coefficients for assessing the significance and relevance of relationships between the constructs (Hair 2017).

Collinearity assessment

The first step in assessing the structural model was to make sure that the structural model did not bias the regression results. This step was done through collinearity assessment. The variance inflation factor (VIF) was used to examine the collinearity (Hair et al. 2019). Table 4.7 summarises the collinearity assessment for the PLS model with satisfactory values for VIF which all are below 3.

Table 4.7 *Collinearity assessment*

Hypothesis		VIF
H1:	Supplier characteristics → Organisational culture	1.000
H2:	Supplier characteristics → Affordability	1.518
H3:	Supplier characteristics → User-friendliness	2.504
H4:	Supplier characteristics → Demonstrated effectiveness	1.000
H5:	Demonstrated effectiveness → User-friendliness	2.459
H6:	Demonstrated effectiveness → Technical constraints	1.025
H7:	Organisational culture → Technical constraints	1.025
H8:	Technical constraints → User-friendliness	1.101
H9:	User-friendliness → Affordability	1.518

Structural model path coefficients

The significance of each hypothesis was examined through path coefficients in the inner model. Estimated path coefficients ranged between +1 and -1. The closer the coefficient is to either boundaries, the stronger is the relationship. Bootstrapping technique gave more clear results on the statistical significance of a structural path at a certain error probability. Common t-values for a two-tailed test are 1.65 for the significance level of 10%, 1.96 for a significance level of 5% and 2.57 when the error probability is 1%.

Two-tailed bias-corrected and accelerated bootstrapping was used for the path analysis of the PLS model. The number of bootstrap samples used was 5,000. Table 4.8 shows the path analysis results, including the path coefficients, t-values for a two-tailed test, and the level of significance for each of the paths. In this regard, all nine hypotheses were supported.

Table 4.8 *Path coefficients and significance*

Hypothesis		Coefficient	t-value	P value	Level of Significance
H1:	Supplier characteristics → Organisational culture	0.233	2.069	0.039	5%
H2:	Supplier characteristics → Affordability	0.229	1.886	0.059	10%
H3:	Supplier characteristics → User-friendliness	0.268	2.272	0.023	5%
H4:	Supplier characteristics → Demonstrated effectiveness	0.769	12.567	0.000	1%
H5:	Demonstrated effectiveness → User-friendliness	0.302	2.479	0.013	5%
H6:	Demonstrated effectiveness → Technical constraints	0.189	2.534	0.011	5%
H7:	Organisational culture → Technical constraints	0.497	5.451	0.000	1%
H8:	Technical constraints → User-friendliness	0.283	3.370	0.001	1%
H9:	User-friendliness → Affordability	0.333	2.455	0.014	5%

4.5.1.6 Ranking of factors and discussion

Ranking of identified factors according to their mean scores can help with a valid interpretation of construction stakeholders' perceptions about the importance of such factors. The mean scores of factors used in the structural equation model ranged from 4.33 to 2.55. The one sample t-test was conducted to determine the significance of every factor against the test value of 2 (factor being slightly important). The value of zero for all 21 factors suggested they all significantly influence the adoption of sensing technologies in construction.

Eight factors out of 21, had a mean score higher than 4 which indicates that the respondents believe they are highly important. These factors (regardless of the sequence) were: "maintenance cost", "proof of effectiveness on trial sessions", "proof of effectiveness in similar projects", "quality training support from the supplier", "quality support from the supplier during maintenance", "easiness of handling data", "simplicity of use", "compatibility with current systems and activities".

The three top-ranked factors were simplicity of use, proof of effectiveness in similar projects, and easiness of handling data.

“Simplicity of use” was ranked the first, indicating it is of high importance for construction professionals to make sure that the new sensing technology is easy to use and does not require much effort after implementation and while in operation. This supports the importance of the “perceived ease of use” as mentioned by numerous of researchers (Goodrum et al. 2011; Lee, Yu and Jeong 2015). More specifically, it has been reported in the case of scanner technology acceptance in construction (Sepasgozaar, Shirowzhan and Wang 2017) and BIM adoption in small and medium size construction companies (Hong et al. 2016). Usman and Said (2012) reported that “operational difficulties” negatively affect the information and communication technology innovation in construction.

“Proof of effectiveness in similar projects” was ranked the second, which shows that the construction professionals were interested in finding successful examples of sensing technologies implementation in other construction projects. This indicates that successful implementation of a new sensing technology in any construction project can positively affect its adoption in other projects and by other construction companies.

“Easiness of handling data” was ranked as the third most important factor, suggesting that data management and post-processing requirements of data is one of the major concerns in sensing technology adoption during construction.

Table 4.9 reports the mean scores, significance and ranking of the factors influencing the adoption of sensing technologies in construction according to the results from the online survey.

Table 4.9 *Ranking of the factors*

Grouping / Indicator	Mean	Significance	Rank
Affordability			
Af1	3.99	0.000	8
Af2	4.09	0.000	6
Af3	3.63	0.000	12
Demonstrated Effectiveness			
DE1	3.83	0.000	10
DE2	4.18	0.000	4
DE3	4.29	0.000	2
Organisational Culture			
OC1	3.65	0.000	11
OC2	3.18	0.000	15
OC3	2.55	0.000	20
Supplier Characteristics			
SCh1	3.95	0.000	9
SCh2	4.06	0.000	7
SCh3	4.13	0.000	5
Technical Constraints			
TC3	3.23	0.000	14
TC4	3.01	0.000	17
TC5	2.68	0.000	18
TC6	3.26	0.000	13
TC7	2.67	0.000	19
TC8	3.06	0.000	16
User-friendliness			
UF1	4.24	0.000	3
UF2	4.34	0.000	1
UF3	4.13	0.000	5

4.6 Summary

This chapter reported the results of two separate sets of analyses of quantitative data collected through an online survey to address objectives 2 and 3. An online survey was employed to collect data on different aspects of sensing technology implementation in construction. Data was collected from 82 surveys completed by Australian construction professionals experienced in using sensing technologies. The current status of using selected sensing technologies that were identified in the literature review was explored by asking about the rates of using particular types of sensing technologies to improve construction safety, productivity or quality. Descriptive analysis on the frequencies of using GPS, RFID, UWB, FOS, pressure sensing, temperature sensing, visual recordings and 3D scanning was done and the current status of these technologies was reported and presented in pie charts (Figure 4.6 – Figure 4.29).

More importantly, 24 factors affecting the adoption of other types of digital technologies in construction were identified in the literature review and pilot study, and were examined with a PLS-SEM path model to confirm if they also significantly affect the adoption of sensing technologies. Disregarding three non-significant factors in preliminary PLS-SEM models, the final structural model consisted of 21 independent variables (factors) within six latent variables (constructs) and nine paths (hypotheses). PLS-SEM results supported the significance of the majority of the identified factors (21 indicators) and all nine hypotheses describing the relationships between the latent variables (factor groupings: affordability, technical constraints, organisational culture, user-friendliness and demonstrated effectiveness).

The results showed that “simplicity of use”, “proof of effectiveness in other projects” and “easiness of handling data” are the top three highly-ranked factors. The results of the path analysis indicated that among all the nine supported hypotheses in the PLS-SEM model, two were showing very high significance: “supplier characteristics” had the highest influence on “demonstrated effectiveness” and then “organisational culture” greatly influenced the “technical constraints”.

Chapter Five

5

Qualitative Data Collection and Analysis

5.1 Introduction

Qualitative research is more than just a non-statistical mode of data collection. Although different epistemological positions and geographical variations attract different alterations to the definition of qualitative research, it is basically a process of naturalistic inquiry that seeks in-depth understanding of social phenomena. It is predominantly inductive and is conducted in natural settings (Klenke 2016). Qualitative research is known as interpretive, inductive and reflexive since it is fundamentally based on communication, and is subjective to the respondents' perceptions and the researchers' interpretive skills (Irene Vasilachis de 2009). Qualitative research can discover new perspectives on what is known or can identify causal explanations on how certain events affect others (Maxwell 2004). Rigorous qualitative studies have several clear advantages over quantitative methods. Examples are being able to understand causation, and to deeply explore leadership and management phenomena through asking "why" questions (Klenke 2016).

Qualitative research employs an approach that is both interpretive and naturalistic, allowing the researcher to study a phenomenon in its natural settings, trying to interpret it in terms of the meanings people bring to it (Jha 2008). A qualitative approach in this present research provided value-adding information from the perceptions of construction professionals, especially construction managers and decision makers who are well experienced in using sensing technologies in their fields of construction. Value-adding information in this regard covers any aspect of sensing technology adoption in construction including the factors preventing and motivating wider adoption of sensing technologies in construction. As a result, this chapter is dedicated to more extendedly addressing objective 3 and would complement the findings from Chapter 4 in regard to the factors affecting the adoption of sensing technologies and the construction stakeholders' concerns about the adoption and implementation of such technologies during the construction phase.

5.2 Qualitative Methods of Data Collection and Analysis

There are various types of data collection methods for qualitative research such as online surveys, questionnaires, interviews, focus groups, observations, etc. Carefully nominating and selecting the most appropriate methods for collecting qualitative data is critical since the methods and expertise required to employ them greatly affect the convergence of collected data (Fellows and Liu 2015). Therefore, it was important to give attention to the most suitable method for collecting in-depth value-adding information on the subject of sensing technology adoption in construction and factors affecting it.

Conducting interviews was reported to be the most common method of data collection in qualitative research (Cassell 2004), which provides an incredibly rich source of data when done well (Daniel 2018). As Fellows and Liu (2015) noted, data collection methods are usually categorised as either one-way or two-way communications. The latter provides opportunities for extended discussions based on interviewees' experience and willingness to share ideas. As a two-way and non-linear communication method, semi-structured interviews are suitable for transferring meanings (Fellows and Liu 2015) and therefore are recognised as the most suitable means of data collection for this research.

It was assumed that semi-structured interviews would facilitate a more effective data collection process since there were opportunities for the interviewees to seek clarification and provide detailed explanations if required. On the other hand, the researcher could encourage interviewees to comprehensively share their concerns, expand the interview questions based on the interviewees' experience and also ask for supplementary information as required per case. This helped with providing a rich source of qualitative data to more extensively address the third objective of this thesis (in addition to the findings from quantitative approach) and also shape the backbone of the governance framework.

A semi-structured interview questionnaire was designed to find out construction stakeholders' and decision makers' experiences, perceptions and attitudes towards sensing technologies. The questionnaire pursued the respondents' points of view on matters that ranged from the extent of sensing technologies implementation in their projects to aspects of construction performance being improved since using them, as well as benefits, risks, limitations and drawbacks that usually come with each sensing technology. Then, factors influencing the adoption of new sensing technologies were explored, along with desired betterment that may lead to a more straightforward adoption and efficient implementation of sensing technologies to improve construction performance.

Notwithstanding the fact that face-to-face semi-structured interviews required a great deal of time and energy in order to collect sufficient data, this method still had major advantages over structured questionnaires since the first priority for the researcher was the quality, originality, integrity and competency of collected data. Besides, the two-way communication during a semi-structured interview provided an opportunity for discussing case-by-case complications as well as generic issues with the application and implementation of sensing technologies during construction processes.

Qualitative data analysis took place through five process stages as Creswell (2018a) has outlined: transcribing the audio interviews, organising transcripts, iterative re-reading of transcripts, coding transcripts and generating themes. The thematic analysis employed in this chapter included categorising detailed information from the interview transcriptions as well as discovering the relevance and causation relationships between the categories to form the themes.

5.3 Data Collection

In this section, various steps that were taken before and during qualitative data collection are outlined and explained.

5.3.1 Pilot interviews

The input to the interview process, ranging from the general structure to clarifications and questions is of high importance as it influences and conducts the responses from the interviewees (Fellows and Liu 2015). To ensure the quality of interview input, three pilot interviews with three construction professionals were carried out initially to assess the integrity, objectivity, profundity and comprehensiveness of the interview questionnaire and to improve it accordingly. The pilot interviewees included a construction manager with 10 years of experience, a site manager with 7 years of experience and a project manager with 5 years of experience. The pilot interviews were carried out in the same way as the actual data-collecting interviews would be, to simulate an actual interview environment for both the interviewees and the interviewer. After each pilot interview, the interviewees were asked to provide feedback on the interview structure, clarity and comprehensiveness of the questions.

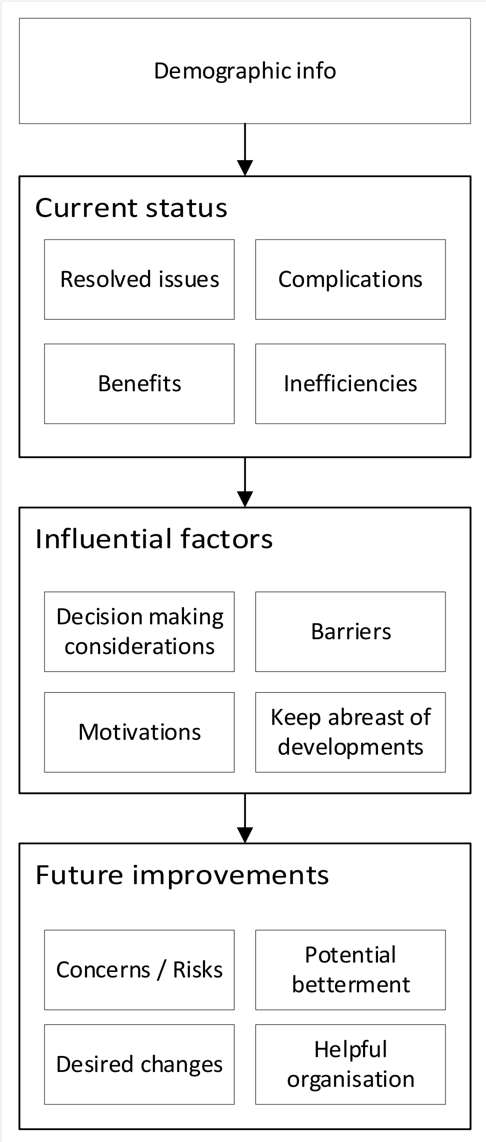
The pilot interviews were audio recorded and transcribed for further analysis. Those pilot transcriptions were quickly analysed for consistency of structure, and feedback from the participants was taken into account to improve the questionnaire. Changes included the sequence of some interview questions, more introductory information within the questionnaire, and a few more questions to obtain more information.

5.3.2 Design of the interview questionnaire

Data collection is a series of interrelated activities that are designed to acquire information to answer a research question (Creswell 2018a). The interview questionnaire used in the current research was designed to be comprehensive yet clear, to attract as many aspects of interviewees' experiences, points of view, concerns and ideas as possible. Four parts inquired into the applications, implementations, benefits and possible issues of new sensing technologies revolutionising some aspects of construction management, ranging from reducing safety risks to productivity improvements and quality assurance.

The first part of the interview sought demographic information including the interviewees' position, experience and type of construction projects they are involved in. The second part focused on the current status of using sensing technologies in construction along with perceived benefits, privileges, resolved issues through technology adoption and possible inefficiencies of sensing technologies in construction. Although the current status of sensing technologies has been addressed in Chapter 4 and was not a subject of qualitative analysis here, it was still important to achieve a clear understanding about the types of technologies that the interviewee was experienced or familiar with. This step was expected to ensure the interviewee and researcher had a common understanding for continuing through the rest of the interview. The third part was about discussing factors affecting the adoption of sensing technologies, decision making considerations, motivations and barriers towards a wider adoption of sensing technologies in construction as well as the way the interviewees were keeping abreast of the latest developments of sensing technologies applicable to their areas. The

Figure 5.1 *Structure of the interview questionnaire*



final part of the interview explored interviewees' concerns regarding the use of sensing technologies, associated risks and possible improvements required towards a wider adoption of sensing technologies in construction, if possible. This section was also inquiring about any organisations or authorities that could help construction companies to improve their performance by adopting sensing technologies more efficiently. Figure 5.1 illustrates the overall structure of the interview questionnaire.

The focus of the interviews was on those technologies employed during ongoing construction monitoring to improve aspects of construction performance and factors associated with their adoption. Hence, well-established and essential sensors were not the primary intention of the current research, although they might have been brought up as examples during the interviews.

As the two last parts of the interview constituted the main focus of this research and would accommodate much of the data for qualitative analysis, most of the focus was on these two sections. Interviewees were encouraged to express their views and perceptions regarding the adoption of sensing technologies and associated factors that might have limited the implementation of sensing technologies in construction.

The interview questions were open-ended to accommodate specific discussions based on every individual interviewee's experiences. Consequently, there were cases in which a question was skipped because the characteristics of a construction project the interviewee was talking about caused a new area of discussion to emerge.

The interviewees were provided with an information statement about the purpose of the research and details about the interview sessions. Before an interview began the purpose of the interview was explained, and clarifications were made in response to interviewee questions. The interviewees were assured of the confidentiality of their information and were asked to give written consent to be interviewed. All of the interviews were audio recorded and transcribed for analysis.

A copy of the information statement, consent form and interview questionnaire are presented in Appendix B, Appendix C and Appendix D, respectively.

5.3.3 Sample size, eligibility and recruitment of participants

As Klenke (2016) mentioned, qualitative research employs purposive sampling. With regard to the present study, participants who could provide in-depth and value-adding information about the adoption and implementation of sensing technologies in construction were intentionally selected. Therefore, eligibility of interviewees was intensively investigated and potential interviewees were contacted accordingly.

The interviewees were selected from construction professionals in the building, oil and gas, mining and infrastructure industries. Eligible interviewees needed to be highly experienced in construction management, very familiar with day to day construction challenges, and be experienced in using sensing technologies to improve some aspects of construction performance.

Various approaches were taken to find eligible interviewees. Snowball sampling, emails and LinkedIn messages were the main recruitment channels. Contact was made with construction professionals who had previously supported research and through personal referrals in snowball sampling. Moreover, construction managers and construction project managers in different sectors of the construction industry were invited through LinkedIn messages to participate in this research. If they were interested and eligible, then they were officially invited to participate in the research. The recruitment process involved emails or LinkedIn messages that explained the nature of the research and invitations to be interviewed on the subject of sensing technology adoption in construction. Participants were provided with information highlighting the purpose of the research, details about the research team, and ethics approval. Participation was voluntary and participants were informed of the confidentiality and anonymity of their responses. Written consent was obtained before conducting the interviews.

Since qualitative research employs purposive sampling, a sample size is defined by the concept of data saturation (Klenke 2016), a point in which additional interviewing results in no additional information. In the current research, the researcher initially projected a sample size of 20–25 interviews provided that the required saturation is met. Qualitative data analysis right after each interview showed a noticeable decrease in the number of new nodes being created after the fifteenth interview. In total, 73 interview invitations were sent to highly experienced construction professionals considerably proficient in using sensing technologies in construction and 21 responses were received which seventeen of them were recognised as eligible interviewees and fitted within the scope of this research. Since the data saturation was met by 17 interviews, no further interview recruitment was pursued. All participants gave written consent to be interviewed and audio recorded. Some interviewees were interested in receiving the interview transcription and research results and some others were not. The researcher contacted every individual interviewee based and according to their preference.

5.4 Data Analysis

The purpose of qualitative analysis of data from interviews is to find the relationships between categories and themes within the context of collected data, with the intention of increasing the understanding of the phenomenon (Alyahmady and Al Abri 2013).

As each interview was completed, the processing of the data began immediately by following the steps recommended by Creswell (2018a) for every single interview. The first step was to transcribe audio recordings of the interviews. Transcription was carried out by online transcription services, followed by manual checking of the transcription text against the recorded interview for required modifications. On a few occasions where high background noises disrupted the interview, transcriptions were done manually by the researcher. Over 550 minutes of voice recordings were transcribed onto 132 pages. For the second step of data analysis, every interview transcript was imported into qualitative data analysis software (NVivo 12 Pro). Iterative re-reading of the transcript provided the researcher with sound understanding and comprehensive insight of each interview and the interviewee's perspective. In the next step, detailed interview discussions were coded and themes created to describe generated nodes. Coding interview transcriptions resulted in assigning 408 passages to 67 nodes and child nodes. More details on data coding and thematic analysis are provided in section 5.4.1.

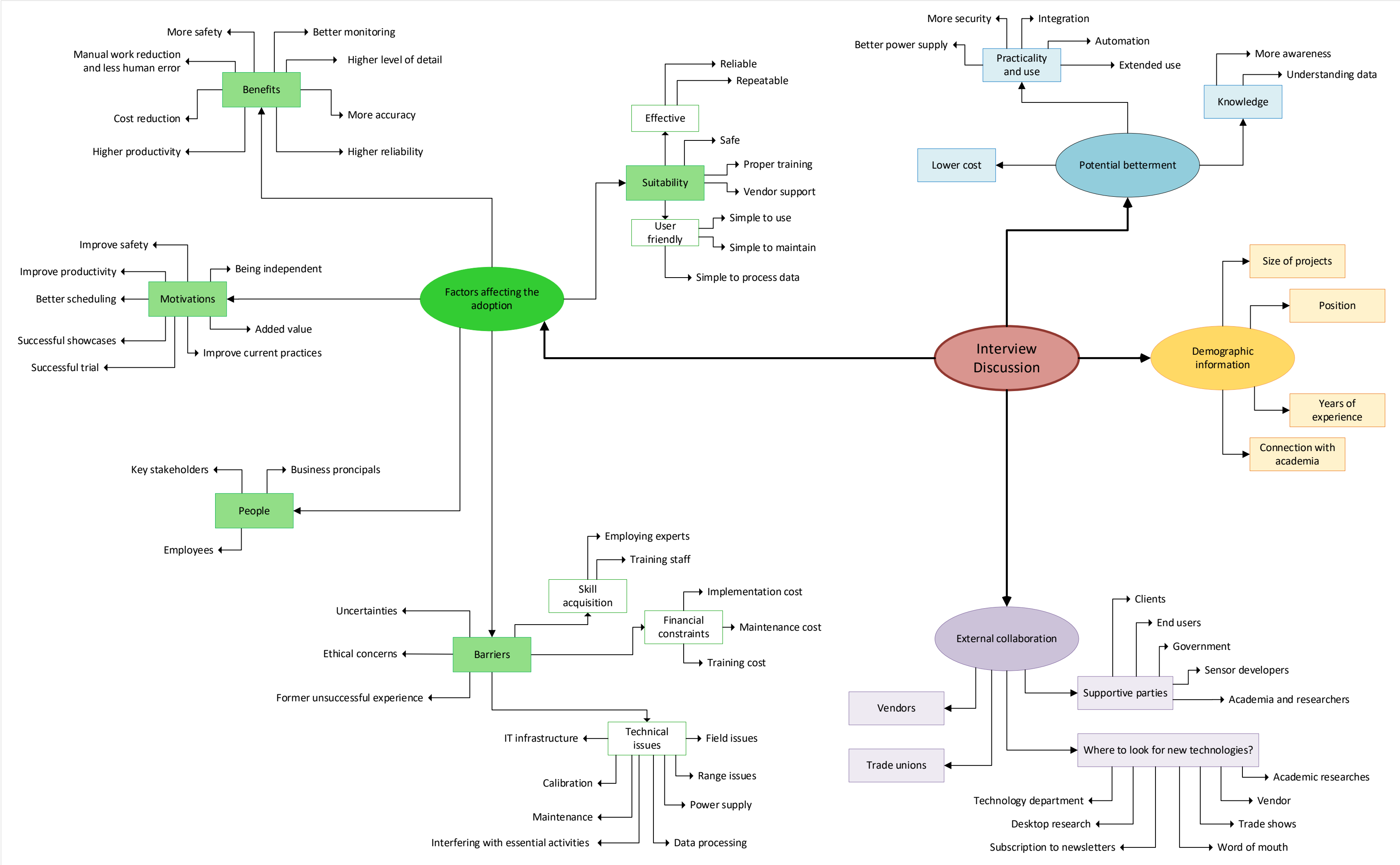
5.4.1 Data Coding in NVivo

NVivo Pro, which was developed to manage coding procedures for data classification and management, is highly regarded for qualitative data analysis (Alyahmady and Al Abri 2013) and was employed for data coding and thematic analysis in this present research. NVivo has been used in a wide range of disciplinary areas to support the analyses of data gathered through interviews, focus groups, documents, field notes and open-ended survey questionnaires (Woods et al. 2016).

Before commencing data coding, the interview transcription was closely scanned to provide a clear picture of the whole interview discussion for the researcher. This initial step involved creating memos as required and exploring best practices for creating nodes and categorising input data. Data coding involved attaching labels to segments of data that depicted what each segment was about. Coding purified and filtered data, sorted it and provided a foundation for comparison between various segments of data (Charmaz 2006). There were distinct levels of coding of the data in this research. The first level of coding was in close relation to the original text and was intended to guide later and higher coding levels. Recoding continued until a satisfactory level of data classification was acquired. In this regard, level one coding of the interview transcriptions was based on the structure of the interview questionnaire, and more detailed coding was based on the content of the interview transcriptions. Subsequent levels of coding and recoding finally provided a sophisticated level of coding that comprehensively covered detailed viewpoints of interviewees. As relationships were discovered, nodes were created and relevant passages (references) assigned to those nodes. The nodes were either predefined or created in response to emerging information in the interview transcriptions. Whenever a few nodes related to a specific concept or area of technology adoption they were categorised into a theme. Eventually, several overarching themes became obvious and assisted data interpretation.

Coding the interview discussions resulted in developing four overarching themes: “demographic information” which provided details on the profile of respondents (see 5.5.1), “factors affecting the adoption” which was the major focus of the interview discussions and embraced the majority of coding (see 5.5.2), “potential betterment” which incorporated potential improvements the interviewees were eager to see in regard to the state of sensing technologies in construction (see 5.5.3), and “external collaboration” which was basically the collaboration between the construction companies and external parties that might affect the adoption of sensing technologies (see 5.5.4). More themes are contemplated in each overarching theme. Figure 5.2 maps the coding of interview transcriptions undertaken for this research.

Figure 5.2 *Map of coding interview transcriptions*



5.5 Results and Discussion

Interpreting the data involved conceptualising a larger meaning of data beyond the codes and themes (Creswell 2013). The interpretive skills of a researcher highly affect the result of data analysis as meanings are abstracted from the context of data to create nodes, then themes, and finding overarching implications.

The results of the qualitative data analysis and interpretation is presented in this section. Firstly, demographic information of the interviewees and their industries is presented to provide a clear profile of participants in this research. Then, the section discusses factors affecting the adoption of sensing technologies along with related limitations, motivations and potential betterment towards a wider adoption of these technologies to improve construction performance. Those factors are presented here according to the nodes and themes that developed from the analysis of the data by using NVivo.

Seventeen face-to-face semi-structured interviews were conducted with industry professionals highly experienced in construction with adequate knowledge and experience in sensing technologies application and implementation during the construction phase in different industries. All the interviews took place at the workplace of the interviewees for their convenience. The duration of interview sessions was different, ranging from 30 minutes to over one hour depending on the interviewee's willingness to share ideas. Thematic analysis of their transcripts is presented below in four separate sections: demographic information, factors affecting the adoption of sensing technologies, potential betterment that were suggested for a more facile adoption, and collaboration with external parties.

5.5.1 Profile of participants

The majority of interviewees (10) were from the oil and gas industry, four worked in infrastructure construction, five were from the mining industry and one was in the building industry. All held top management positions including directors, site superintendents, construction managers, project managers, technical managers, health and safety managers, environmental and quality managers, surveyors and engineering leads. Their years of experience in construction ranged from 10 years to more than 40 years, with an average of more than 20 years of experience. The participants had extensive experience in using one or several sensing technologies during construction in their industry.

It is worth mentioning that all of the interviewees were from big construction companies involved in mega projects of millions to billions of dollars in value. Seven participants declared that they had been previously involved in academic research studies on new technologies. Five participants had the experience of playing a fundamental role in research projects with universities that involved sensing technologies. The other interviewees (10) said this was their first experience of participating in research. Table 5.1 gives details of interviewees' demographic information.

Table 5.1 *Profile of interview participants*

Industry	Position	Previous participation in academic research	Minimum years of experience in construction
Oil and gas	Project director	Yes	40
	Technology director	Yes	30
	Construction manager	Yes	30
	Construction manager	No	20
	Integration manager	Yes	20
	Technical manager	Yes	30
	Field engineering lead	Yes	35
Mining	Project manager	No	15
	Lead engineering manager	Yes	11
	Site superintendent	No	10
	Construction manager	No	10
	Survey manager	No	19
Infrastructure	Construction manager	No	11
	Quality manager	No	25
	Environmental manager	No	10
	Survey manager	No	11
Building	Regional health, safety, environment quality manager	No	30

5.5.2 Factors affecting the adoption and implementation

One major objective of interviewing construction professionals was to identify factors affecting the adoption and implementation of sensing technologies in construction, such as barriers and limitations, motivations and incentives towards procurement, and introduction of a new sensing technology into the business as a standard practice on construction sites. The interview pursued this objective by asking these highly experienced construction professionals open-ended questions about decision making considerations for the adoption of sensing technology. Explicitly, the applications, advantages and benefits of sensing technologies in the context of construction management were raised and discussed, as well as probable inefficiencies, complications or impediments that hindered sensing technology adoption.

As a result of coding and recoding the data in NVivo, 295 passages of text relating to factors influencing technology implementation were identified and assigned to 48 nodes. A few nodes that represented a mutual concept were assigned to a parent node. For example, the three nodes of investment cost, training cost and maintenance cost were all assigned into a parent node named "Financial Constraints" since they all were budget related factors.

These 48 nodes were then grouped into five overarching themes, each related to a different aspect of sensing technology adoption. These five themes are: benefits, barriers, suitability of the technology, motivations, and people's attitude. Each theme and their associated nodes are discussed as follows.

5.5.2.1 Benefits

Benefits resulted from proper implementation of them during the construction phase were extensively discussed during the interviews. These benefits are the advantages gained from adopting the new sensing technology as opposed to the traditional practices. Of all references to factors affecting the adoption of sensing technologies in construction, most were related to benefits, with 101 references (passages) across all 17 interviews. This indicates the interviewees were well aware of the benefits of sensing technologies in construction. Eight independent nodes of recognised benefits associated with using sensing technologies in construction were identified.

More safety

Achieving a higher level of safety in construction is the primary benefit identified through the qualitative analysis. Across 15 interviews, 31 references were made to the benefit of safety. For example:

> "…it gives us obviously a much safer place to be operating the equipment we need to use…".

> "…the key advantage for us in terms of improving safety is the ability to use a remote system to orientate loads versus the traditional methods...".

Higher productivity

More productive construction process is the second most noted benefit of using sensing technologies. There were 22 references to this factor from 12 interviews, particularly as a method of improving construction productivity through tracking technologies to monitor supply chain and material deliveries.

> "Being able to find something that would otherwise be lost…So tracking them having active tags on them or having passive tags on them…it doesn't stop it (losing materials or resources) but it helps minimise it. And if it does happen you quite often will find out that you don't have what you thought you would…You can scan that box and see all the different things that are tagged in there."

Better monitoring

Twenty references from 11 interviews noted that sensing technologies can assist with better monitoring of construction processes or requirements.

> "We use it for inspections as well…scaffolding also required to be inspected on some construction projects every week…every particular entry point on a bit of a scaffolding have an RFID tag and then an inspector goes with a tablet to scan RFID tag and see all the history of that particular construction…".

> "They give us more details and thus more confidence in what we're dealing with. The monitoring is much easier and quicker. And based on more information we receive from these technologies we make better decisions."

> "…the noise and dust (sensors) and those sorts of things…definitely effective we know where we've got an issue we can quickly identify with either exceeded or not exceeded. So when it comes to complaints or damage that comes into it...".

More accuracy

Seven interviewees made 9 references to sensing technologies providing more accuracy in the job.

> "…you've got a lot more clarity and detailed knowledge there which means you can fine tune things…".

Manual work reduction and less human error

Manual work reduction and consequently less human error and less rework was another benefit of automated data collection as indicated by 6 interviewees.

> "…if you've got physical data that you can use to track and compare one point to another, it removes the dependency on human assessment…".

> "You're exposed to human error…So by actually implementing GPS. you know it saves a lot of time and cost…as long as the data is uploaded properly into the machines…".

Cost reduction

Another benefit, cost reduction, was made in in 6 references from 3 interviews.

> "…reduce cost; because you haven't lost equipment therefore you've saved… you've prevented losing money. So that's a benefit to the project...".

Higher level of detail

Sensing technologies provide higher levels of detail as specified by 4 interviewees. One interviewee indicated that:

> "The detail of information is there…if you've got a lot more clarity and detailed knowledge there which means you can fine tune things and look at things and say look we can do this we can have this…".

Higher reliability

Using sensing technologies might make the work more reliable as 3 interviewees pointed out. As one example:

> "…we need things to help us know that we are doing the right thing at the right place at the right time and the moisture sensors will be the one where the inputs we will use to help us prioritise our work…".

5.5.2.2 Barriers

Barriers are those challenges or limitations that prevent the construction companies from adopting sensing technologies. The theme of barriers to adopting technology was the second most noted concern: 16 interviewees made 74 references. Although most references were made about the benefits of sensing technologies in construction, it is clear that the interviewees were concerned about barriers that might hinder them from achieving such benefits.

Nineteen nodes with a theme of barriers include three parent nodes, 13 child nodes and three independent nodes.

Technical issues

There were 30 references across 11 interviews to the parent node of technical issues. Child nodes of technical issues were defined as: “field issues”, “range issues”, “power supply”, “data processing”, “maintenance”, “calibration”, “IT infrastructure”, and “interference with essential activities”.

> “If you have a system and you want to then add tracking to that or tools you have to make sure it's compatible…you're relying on that to give you good information but you didn't realise that if you take it into a different environment it may mess up the calibration or it may not read correctly then it can impose a risk… for instance things going out of range… the battery has to last long enough to be able to do it…”.

> “…there's some restrictions on using certain frequencies because of radios or because of other equipment”.

> “…we found that it just wasn't right…it worked well in the lab but it didn't work in the field. It was just too susceptible to noise...the results were a mixture of under recording and over recording…”.

Financial constraints

Financial constraints as the second most noted barrier with 21 references from 9 interviews were categorised into three child nodes: “implementation cost”, “training cost” and “maintenance cost”:

> “…cost is a major one, well you can have a wonderful technology but it's too expensive…it seems so the primary one is the cost benefit curve… t's always down to how much is it going to cost and what benefit does it bring… maintenance cost is a big thing you know it's no good putting in something now that needs to be replaced in three or four years…”.

Uncertainties

Six interviewees made 9 references to uncertainties about new sensing technology, its fitness for the job, and adaptability to site characteristics as major barriers to proper implementation. Here is an example of concerns mentioned by an interviewee with 35 years of experience in construction:

> "Do they actually live up to their certification? Are they reliable? What if we start relying on their results and we find they're not repeatable or they fail in a way that gives us the answer that we're looking for and it's not…".

Ethical concerns

Four of the interviewees made 6 references to concerns about individual privacy and ownership of data when people were somehow involved in data collection.

> "…there's a lot of public backlash against drones like we've done a lot of drone surveys close to residential subdivisions and you get a lot of public backlash…".

> "Photographs for example…we've got to get permission from people before we can actually take photographs...".

> "…two or three years ago we introduced access controls onto site. We had a massive keep back from the union because people were tagging in and out...".

Skill acquisition

Skill acquisition was defined as another parent node, with child nodes identified as "training staff" (raised by 3 interviewees) and "employing experts", mentioned by 2 interviewees.

> "…one of the biggest issues is most certainly getting competent skilled workforce that's motivated…".

> "…I guess just learning them really (is a challenge). Learning new technologies and having the time to undertake training…".

Former unsuccessful experience

Two of the interviewees mentioned how their former unsuccessful experience with innovative technologies caused some resistance to accepting new sensing technologies.

> "It was just too susceptible to noise and vibration…the results were a mixture of under recording and over recording. So we overreacted in places where we shouldn't…It caused us to not trust that technology for maybe longer than we should have not trusted it."

5.5.2.3 Suitability of the technology

Desired attributes for a suitable sensing technology formed the theme of suitability in thematic analysis of qualitative data. Suitability of the technology with 59 references was the third most noted concern regarding sensing technology adoption in construction. The words of a construction manager with over 20 years of experience sums up the opinions that were expressed about the suitability of sensing technology to the nature of construction work and site characteristics:

> "What exactly do construction sites need from sensors that they don't have today?"

Ten different nodes were defined within this theme including two parent nodes and three independent nodes. The two parent nodes are:

Effective

Being effective to improve construction performance is an attribute that makes a sensing technology suitable for the job. This node attracted 26 references from 14 interviews, inclusive of two child nodes: "Reliable" (10 references from eight interviewees), and "Repeatable" (only one reference).

User-friendly

There were three child nodes: "simple to use" (with 8 references from 5 interviews), "simple to maintain" (2 references mentioned by 2 interviewees) and "simple to process data" (1 reference).

The three independent nodes are: "being safe" for the construction site (15 references from 8 interviewees), "proper training" (6 references from 5 interviewees) and "vendor support" (1 reference).

Being safe for the construction site is a requirement mostly mentioned by interviewees from the oil and gas industry as hydrocarbon processing facilities demand intrinsically safe equipment.

> "If you don't have intrinsically safe equipment then you need more permit considerations…explosion proof equipment and intrinsically safe equipment is the preference. Even the tablets we use have a level of intrinsic safety…".

5.5.2.4 Motivations

Motivations persuade construction companies to adopt new sensing technologies to improve some aspects of construction performance. Various motivations for adopting new sensing technologies in construction were detected in the analysis of the interview transcriptions. Overall, 40 references related to motivations were detected in 14 interviews and assigned to eight nodes.

Improve productivity

Improving construction productivity has been recognised as the most noted motivation initiating sensing technology adoption and implementation. The concept of improving productivity as a result of using sensing technologies was mentioned by 10 interviewees over 17 occasions.

> "Anything that'll help demonstrate some productivity gain and efficiencies. Definitely our business will be interested…if they could see some of these technologies that will help make the work efficient."

> "Anything that helps to improve our efficiency and reduce the cost of these projects is going to be beneficial to the business as a whole…our efficiency and productivity is something that lays behind. It definitely needs improvement."

> "…but also the benefit: we're starting to see you know time savings as well…".

Improve safety

Improving safety is the second most noted motivation identified with 7 references from 6 interviews. The reason that improving construction productivity was noted in advance of improving safety does not mean that productivity is more important than safety but, rather, that there is a greater need to address productivity issues, as safety has always been a centre of attention in both research and actual projects and there are regulations specifying some requirements to maintain an acceptable level of safety. This was explained by an interviewee in this way:

> "I think the industries as a whole, in its history, people got hurt and it doesn't take much to understand that people getting hurt then we're not going to improve, we're not going to have our projects being approved because of the risk to people. So yes that (safety) takes a priority and research flows mostly through that, but we do manage to monitor safety very well, that continues to be focused. However, our efficiency and productivity is something that lays behind. It definitely needs improvement."

Better scheduling

Better schedule monitoring and meeting the schedule was a motivation to adopt suitable sensing technologies as mentioned by 4 interviewees. One of the interviewees said: "*Schedule, because you know where your things are and you know that they're on time. It allows you to stay on schedule because everything is there…"*.

Added value

Added value to the project was mentioned as a motivation by 3 interviewees: "…so the biggest frustration for everything is what our return on the investment is. What are we getting out of it? What value does it add or doesn't add?"

Successful trial

Using a new sensing technology during trial sessions to see how fit the technology is for the intended purpose can be a motivation as mentioned by 3 interviewees.

Being independent

Independence from third parties was identified as a motivation by 2 interviewees. "…being independent so not having to approach with third party consultants is definitely a motivation."

Successful showcases

Two interviewees recognised successful examples of previous use as a motivation: "…what will motivate them is when it's being widely adopted…so examples of use..."

Improve current practices

One interviewee twice mentioned a motivation was improving current practices in construction.

5.5.2.5 People's attitude

People's attitude towards sensing technologies has been recognised as an important aspect affecting the adoption of sensing technologies in construction. Since these technologies are relatively new, especially within the context of construction management, some level of resistance might be expected from either key stakeholders or employees. Attitude attracted 21 references within an independent node regarding "business principles" with 8 references, and a parent node about "resistance to change" between either the "key stakeholders" (9 references) or "employees" (4 references).

Resistance to change was raised by 7 interviewees as a major barrier to sensing technology adoption in construction.

> "…The acceptance of people, or the resistance of people to change. So if you could convince people to be open and adopt new things and to look at the bigger benefits…".

> "…if I could change one thing, it would be the clients' willingness to upfront to make that investment".

> "…the hardest thing is trying to convince people…the other thing is to change the attitudes around it…".

5.5.3 Potential betterment

The fourth part of the interviews was dedicated to discussion about "potential betterment" in any aspect of sensing technology adoption in construction. This part accommodated any alteration and improvement that the interviewees were eager to see in regards to the application of established sensing technology or the process of adopting and introducing a new sensing technology into construction practices. Potential betterment, as opposed to benefits, are not proven advantages resulted from the implementation of sensing technologies in construction, but possible changes and future improvements suggested by the interviewees to improve either the application of the sensors or the adoption of the technology.

Coding the interview transcriptions, 43 passages mentioned the improvements required for better adoption or getting the most out of existing sensing technologies. Taking the same steps as mentioned in section 5.5.2, eight nodes were defined and sorted into three themes: "practicality and use", "knowledge", and "lower cost".

5.5.3.1 Practicality and use

The majority of potential betterment (20 references) identified in the interview transcriptions were about aspects of practicality and use of sensing technologies in construction. Five child nodes were defined in the context of practicality and use as being: "extended use", "automation", "integration", "better power supply", and "more security".

Extended use

Nine references were made to a desire to see wider use of existing sensing technologies, such as wider utilisation of GPS and RFID for tracking material, equipment and even workforce in hazardous areas, and RFID badges for location access, logging into construction equipment, and recording time, location and work. Another mention was the use of proximity detection and anti-collision systems on heavy machinery:

> "I would add an anti-collision system on every vehicle, because there are a lot of fatalities, problems and injuries because of those type of accidents that can be prevented by applying new technologies."

Integration

Integration of several sensing technologies into one multidisciplinary system capable of addressing issues across various disciplines was identified as an important desired improvement in the field of sensing technologies in construction. This meant moving towards the goal of having a unified and integrated sensing system capable of supporting multiple disciplines.

> "Anything that you make which is generic, that interfaces with other (systems). It doesn't tie to specific systems or so forth. It can work in most environments. Because as we go forward and we use more and more devices and more and more sensors and we link more and more sensors and we use the information from these sensors into the systems and tools... In order for it to be simple and in order for you to be able to build these big complicated systems it needs to connect with everything and not cause islands or not cause discontinuities. So your equipment that you add should not isolate other bits or cause links or problems or anything like that."

Automation

The need for some level of automation in construction was identified as a potential betterment in the future by 3 of the interviewees, indicating that the construction industry could benefit from automated field data collection or even autonomous or semi-autonomous equipment, if modified and adjusted to the requirements for the construction industry and fit on construction sites.

> "I will look at autonomous machines in mining. I still believe that eventually on large scale Greenfield projects to be able to use autonomous machinery to do all the civil work, reducing the number of people on site... So autonomous machines and also some robotic type construction aids in

> implementation … I think the technology is there. Just trying to develop the suitability of that technology to our business. And the machinery, they can use that technology. So again, you look at dump trucks, they're now autonomous. That was a big step and a very expensive learning exercise. You look at the civil equipment, I believe that can be done. I think they started the journey, but it's now time and investment on that side."

The two final child nodes in this theme of practicality and use referred to the need of "better power supply" before recharging is needed, and "more security" against hackers and malware.

5.5.3.2 Knowledge

A promising theme of factors regarding potential betterment in the adoption and implementation of sensing technologies in construction was identified as "knowledge" of the technology. While coding the interview transcriptions, 15 passages were identified that discussed different knowledge-based factors towards a wider use of sensing technologies in construction. These factors were "more awareness" towards the existence of various types of sensing technologies and their applicability and benefits in construction and "understanding data" to get the most out of the technology.

Seven of the interviewees mentioned the need for more awareness around new opportunities for innovative sensing technologies in construction on 12 occasions emphasising the importance of educating people in the construction industry about the existence and benefits of such technologies and the impact that these technologies could have on enhancing and improving construction processes.

> "I would say improve the awareness of all the options so communicating... that gives an opportunity to make it clear that there are people interested in trying to learn more about these (sensing technologies) and engage the industry... And then we have that in a construction management forum either in the business itself so that the key representatives in the construction organisation of (the company) learn a bit and then they can share with the employees or some sort of workshops or some sort of interactions between academia and business."

> "It's educating people to what's the values and things it's making it easy to understand and to use and to implement. Because if you put barriers in any place with any of these things it makes it hard and so hard to get people to understand. You have to allow the information to flow and you have to let them see the benefit and bring them along the curve and spend the time. And then in order to spend the time you need to have the money and the support to be able to educate and commit."

One construction manager shared his experience of the lack of knowledge as the main reason for the required budget not being allocated for a specific sensing technology:

> "And knowing about this (the existence of such technology) before we start projects, so with (this particular technology), we've got projects going but that have made no allowance to pay for that cost (at the time) because they didn't know about it."

The importance of changing people's mindset to more openly accept new technologies was brought up by some interviewees as a key component to accommodate a more straightforward adoption of sensing technology.

> "With the construction culture it's really changing their mindset of embracing new technology."

> "I think if I could change one thing it would be the clients' willingness to be upfront to make that investment (to employ the sensing technology) … I would want the clients to be more willing to adopt it at the senior level to say yeah we'll make an investment for this and see if it works."

And finally, understanding collected data and being able to interpret it correctly and use it properly was the other aspect of knowledge required for easier technology adoption. One of the interviewees with 40 years of experience in construction observed:

> "It's around understanding the data that you get really and how we're going to use that data … probably establishing the proof and the evidence to people that wow this is good data you should use this …".

5.5.3.3 Lower cost

A lower cost, especially with regard to capital cost at the time of technology procurement, was recognised as a potential encouragement for construction stakeholders to try new sensing technologies and begin to see the benefits. Six of the interviewees noted that with a lower implementation cost, more construction companies would be able to try innovative sensing technologies that might be useful to their businesses. Since the high cost of technology implementation was also mentioned as a major barrier for some construction companies to uptake new sensing technologies, it is not surprising they would like to see a lower implementation cost. Therefore, lower cost was a potential betterment to encourage the adoption of sensing technologies:

> "If they (the new technologies) weren't so expensive, as you move forward cost comes down (but that is not the most recent technology anymore). That's probably one of the biggest inhibitors just the initial cost. If it wasn't so expensive, you know (for) both construction managers and the guys that have to approve the use, it would be easier."

5.5.4 External Collaboration

A wide range of interview discussions were around collaboration with external parties. Seventy passages were identified from 15 interviews that talked about external collaboration in sensing technology adoption during construction. Four separate themes were defined to categorise the 70 references on external collaboration.

5.5.4.1 Looking for new technologies

Sources of information to keep abreast of the latest sensing technologies in the field of construction management was identified as usually being a combination of the following: "word of mouth", "vendor", "desktop research", "subscription to newsletters", "technology department", "trade shows" and "academic research".

> "…our technology department obviously which is very well supported by our company…also being in touch with the universities and our leading contractors that are continuing to evolve and develop, because they're normally at the forefront of development and improve…besides, oil and gas expos generally have quite a few companies that are pushing the boundaries of technology…… so it's about understanding the market place, and the landscape that we're trying to match universities with construction companies with our assets…so it's a combination of a few things and also looking at diversity, looking at technologies used in other businesses that we can adapt to our business…".

> "…most of the time it's you that are going searching for, because usually by time the information gets out to the industry whereby people can come and see you it's already well down the path and you've already made or should have already made your mind up…not always but the majority of time we search for what we need and we use people that we have who are keeping tabs…".

> "We have a technology group is the short answer to that…not only we do hear about it ourselves in talking to people in the industry, our contractors are constantly offering us something bright and shiny particularly if they can get us to adopt their solution to the generic industry issues and lock us into their technology…and we have a technology group who was working on that kind of thing...if it's not something we're generating it's through trade shows and going to talking to suppliers or a supplier comes to us…".

5.5.4.2 Supportive parties

According to the interviewees, supportive parties could influence wider adoption of sensing technologies. These supportive parties were identified as: end users, government and ministerial authorities, sensor developers and suppliers, academia and researchers and clients. The majority of the interviewees believed that sensor end users (construction companies) can provide the most constructive feedback to suppliers in order to improve the technology and make it more suitable for construction sites, while also demonstrating how effective the technology is for improving construction performance.

> "…the best people who understand it are the people who are living it every day. So you want to get in to their hands. They're using it and know the pros and cons of it so you have to get the feedback on it from them…".

5.5.4.3 Vendors

Although the interview questionnaire was not specifically inquiring about the role of vendors in sensing technology adoption, a few of the interviewees emphasised the importance of vendor support and the level of communication with vendors and suppliers. Therefore, external collaboration with vendors is recognised as an important factor that can affect technology adoption by offering and providing technical support during the implementation, operation and maintenance.

> "…vendors being over promise…sometimes we procure something with the promise of delivering or simple installation. But it is noticed that the installation or maintenance of that technology actually required heavily skilled technical experience which we didn't have. So that would have introduced additional cost to operation which was not very pleasant to understand after the procurement of the technology…".

5.5.4.4 Trade unions

One of the interviewees working in building construction pointed out that if using sensing technologies involved data collection from people, trade unions could raise concerns and impose some complications to the process of sensing technology adoption:

> "…from the union's perspective monitoring anything is a problem…two or three years ago we introduced access controls onto site. We had a massive keep back from the union because people are tagging and tagging out…"

5.6 Summary

This chapter presented and discussed the method and materials for qualitative data collection and analysis in order to complement the findings of the quantitative method regarding the factors affecting the adoption of sensing technologies in construction (presented in section 4.5) and more extensively address objective 3. In order to gain an in-depth understanding of construction stakeholders' perceptions about sensing technologies and relevant opportunities in construction projects, a qualitative method of data collection was selected to seek detailed explanations regarding the reasons behind slow adoption of sensing technologies in construction. As a result, 17 semi-structured interviews with highly experienced construction managers and decision makers were conducted, inquiring into factors that might affect the adoption of sensing technologies in construction. Qualitative and thematic analysis of interview transcriptions was done using NVivo Pro. Aside from the demographic and general information on the profile of respondents, 408 passages or references were identified relating to aspects of sensing technology adoption and application in construction. All the references were categorised into relevant nodes, either independent nodes or parent nodes with assigned child nodes. The nodes were categorised into 12 themes and again into three overarching themes as shown in Figure 5.1. The three overarching themes were defined as: factors affecting the adoption and implementation, potential betterment and external collaboration. The majority of passages were related to the factors affecting the adoption. This overarching theme embraced themes of benefits, barriers, suitability of the technology, motivations and people's attitude. Each theme and associated nodes were explained, quoting examples from interviewees' comments to support the researcher's interpretation of interview transcriptions and subsequent thematic analysis.

Chapter Six

6

Development and Validation of the Framework

6.1 Introduction

As the results of quantitative and qualitative analyses were presented in Chapter 4 and Chapter 5 respectively, and the third research objective addressed through both, it is now time to use the results from both methods to address the fourth and last objective of this research. This objective demands a governance framework to accommodate different aspects of sensing technology adoption to cover important factors influencing sensing technology adoption in construction. The governance framework is envisaged to highlight the benefits from adopting and implementing innovative sensing technologies, to foresee possible risks, and generally facilitate sensing technology adoption decision making. Hence, the purpose of this chapter to collate and combine identified factors from both approaches into a unified system to develop the governance framework. Once the framework is evaluated and validated by construction professionals, objective four is addressed and the research aim is met.

This chapter will detail the triangulation method to combine all factors. Likewise, the process of framework development and the evaluation of the framework will be explained. Finally, two supplementary frameworks are also developed in addition to the governance framework. These two frameworks are extracted from the governance framework to emphasise specific aspects of sensing technology adoption and implementation.

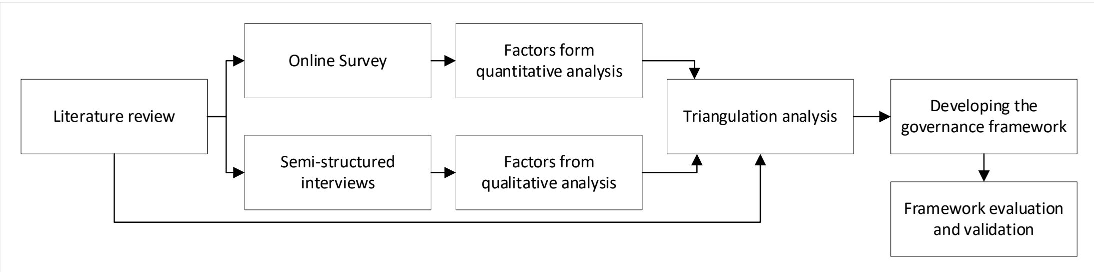
6.2 Triangulation Analysis

A multi-method approach or use of two or more research methods to investigate a single research question is traditionally called triangulation. However, it is now more of a pluralism that involves the adoption of two or more approaches to data collection, analysis and—occasionally—more than one paradigm, theory or philosophy (Fellows and Liu 2015).

In this research, triangulation analysis was used to integrate findings from the literature review with the results of both quantitative and qualitative approaches in order to achieve a more rugged outcome and unbiased inferences, by eliminating or reducing usual disadvantages of single techniques. In this regard, structural equation modelling of the quantitative data provided a base to examine if factors affecting the adoption of other types of IT-based technologies are also significant in the context of sensing technology adoption. Semi-structured interviews went beyond the extent of factors identified in the literature review, and provided the researcher with more expanded yet detailed information from construction stakeholders with hands-on experience with sensing technologies.

The aim of the triangulation analysis was to strengthen the input into the governance framework, which accommodates various streams of factors affecting the adoption of sensing technologies in construction. To achieve this, significant factors from the quantitative analysis were first considered as the initial input to triangulation, and the remaining factors from the qualitative analysis were entered into the triangulation to reflect more in-depth and detailed information on sensing technology adoption. In other words, factors that were statistically significant in the PLS model (Chapter 4) formed the primary input, and were consolidated by the factors extracted from thematic analysis of the interview discussions (in Chapter 5). The combination of the two approaches was then cross-checked against the literature review and strengthened by any overlooked factor. Figure 6.1 depicts how the triangulation method was used to combine quantitative and qualitative results for input into the governance framework.

Figure 6.1 *Triangulation method for developing the governance framework*



6.2.1 Input from quantitative analysis

As established in Chapter 4, 21 factors significantly affected the adoption of sensing technologies in construction. The exact same factor or an equivalent terminology for some of them was used in triangulation analysis for the sake of conformity with results from qualitative analysis. Table 6.1 illustrates equivalent terminology for significant factors affecting the adoption of sensing technologies extracted from quantitative analysis and used in triangulation analysis.

6.2.2 Input from qualitative analysis

Chapter 5 identified factors that influence the process of sensing technology adoption and decision making according to construction professionals' perception of these technologies. All relevant nodes from the qualitative analysis for the triangulation analysis were compared and collated against those of the analysis of the survey. As a result, factors that were duplicated in both methods were excluded and the remainder used as supplementary factors to the framework. It goes without saying that duplicated factors supported by both methods were only considered as results of the survey analysis in the framework input. As in section 6.2.1, the same factor or equivalent terminology was used to ensure consistency in the terminology used to build the framework. Table 6.2 summarises factors only mentioned in the qualitative analysis.

Table 6.1 *Input factors to governance framework from survey analysis*

Factors from quantitative analysis (terminology used in Chapter 4)	Equivalent terminology used in triangulation analysis and framework development
Implementation cost	Implementation cost
Maintenance cost	Maintenance cost
Skill acquisition cost	Skill acquisition cost
Organisational support and approval	Organisation support
Acceptance between employees	Employees' acceptance
Ethical concerns and privacy of employees	Ethical concerns
Reputation of the supplier	Supplier's reputation
Quality training support from the supplier	Supplier's training support
Quality technical support from the supplier during maintenance	Supplier's maintenance support
Easiness of handling data	Ease of data processing
Simplicity of use	Ease of use
Compatibility with current systems and activities	Compatibility with current systems
Proof of effectiveness from other industry parties	Claim of effectiveness by others
Proof of effectiveness on trial sessions	Pilot or trial sessions
Proof of effectiveness in similar projects	Proof of effectiveness in other projects
Effectiveness issues	Lack of effectiveness
Not adaptable with IT infrastructure	Lack of compatibility with IT infrastructures
Hard to get quality technical support	Lack of technical support
Hard to manage and analyse too much collected data	Data processing and management issues
Hard to get quality training	Quality training
Hard to maintain	Maintenance issues

Table 6.2 *Input factors to governance framework from interview analysis, excluding duplicated factors*

Factors from qualitative analysis (terminology used in Chapter 5)	Equivalent terminology used in triangulation analysis and framework development
Business principles	Business principles
More safety	More safety
Higher productivity	More productivity
Improve current practices	Improve current practices
More accuracy	More accuracy and reliability
Better scheduling	Better scheduling
Better monitoring	Better monitoring
Higher level of detail	Higher level of detail
Cost reduction	Cost reduction
Manual work reduction	Manual work reduction
Less rework	Avoid rework
Less human error	Avoid human error
Automation	Automated data collection
Successful showcases	Industry proven showcases
Added value	Added value
Being independent	Being independent
Return of investment	Return of investment
Filed issues	Filed issues
Range issue	Range issue
Power supply	Power supply issues
Calibration	Calibration issues
Uncertainties	Uncertainties
Former unsuccessful experience	Former unsuccessful experience
Safe	Not safe for the construction site
Interfering with essential activities	Interfering with essential activities
Filed practicality	Filed practicality
Reliable	Reliability
Repeatable	Repeatability
Security	Security of the system and collected data
Simple to maintain	Ease of maintenance
Employing experts	Expert availability
Integration	Integration
Vendor support	Vendor/Supplier
Key stakeholders	Key stakeholders
Resistance to change	Resistance to change
Ethical concerns	Privacy policies
Knowledge	Education and awareness

6.2.3 Input from the literature

The combined results from Chapter 4 and Chapter 5 were used as input data to develop the governance framework to accommodate as many factors affecting the adoption of sensing technologies in construction as possible. A total of 21 factors from the survey analysis and 37 factors from the interview analysis were used to establish the governance framework. Combined factors were then compared against the literature review to see if any factor was missing in the triangulated results of the two approaches. Consequently, only two factors were found in the literature review that were not covered by either the quantitative or qualitative results. These two factors were the "durability" of the devices and the benefit of having "real-time data", which is intrinsic to using sensors. These two factors were identified in relation to the adoption of some types of sensing technologies in the literature. All other factors that were reported regarding the adoption of other technologies in the literature, were not considered in this section. Those factors were mostly examined through the quantitative analysis and were reported in section 6.2.1, if showed significant in the PLS-SEM model.

6.2.4 Categories of combined factors in triangulation

The aim of triangulation was to combine all factors from various sources to consolidate the input for the governance framework. However, all the factors presented in sections 6.2.1, 6.2.2 and 6.2.3 should be categorised for functional presentation and practical placement in the framework. Table 6.3 shows the categories created from the triangulated results. In this table, six categories cover all the results from the triangulation method plus "business principles" which is considered as a category of its own, since it governs most policies and actions around new sensing technology adoption in an organisation. The factor for the role of "vendor or supplier" is also considered as a separate category for relevant factors.

Table 6.3 *Categories for triangulated factors*

Category	Factors
Benefits and Motivations	Real-time data
	More safety
	More productivity
	Improve current practices
	More accuracy and reliability
	Better scheduling
	Better monitoring
	Higher level of detail
	Cost reduction
	Manual work reduction
	Avoid rework
	Avoid human error
	Automated data collection
	Industry proven showcases
	Added value
	Being independent
	Proof of effectiveness in other projects
	Claim of effectiveness by others
	Pilot or trial sessions
Barriers	Field issues
	Range issues
	Power supply issues
	Calibration issues
	Uncertainties
	Former unsuccessful experience
	Not safe for the construction site
	Interfering with essential activities
	Lack of compatibility with IT infrastructures
	Data processing and management issues
	Maintenance issues
	Lack of effectiveness
	Lack of technical support

Category	Factors
Considerations	Durability
	Field practicality
	Reliability
	Repeatability
	Security of the system and collected data
	Ease of maintenance
	Expert availability
	Integration
	Ease of data processing
	Ease of use
	Compatibility with current systems
	Quality training
Whole of life cost	Implementation cost
	Maintenance cost
	Skill acquisition cost
	Return of investment
People and organisation	Organisation support
	Employees' acceptance
	Ethical concerns
	Key stakeholders
	Resistance to change
	Privacy policies
	Education and awareness
Vendor / Supplier	Supplier's reputation
	Supplier's training support
	Supplier's maintenance support
Business principles	Business principles

6.3 The Governance Framework

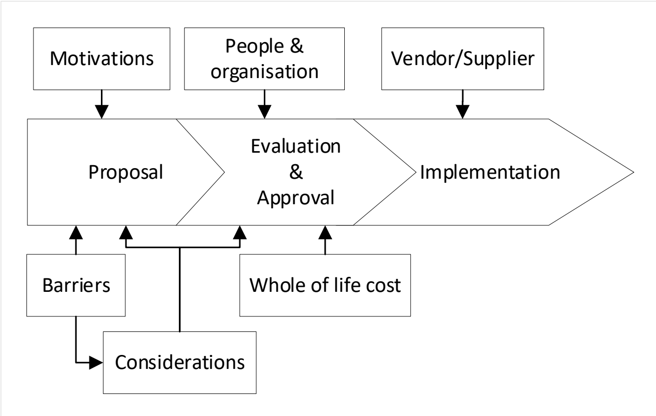
The aim of the governance framework is to include as many important factors affecting the adoption of sensing technologies as possible to highlight benefits of sensing technology implementation, anticipate possible complications to mitigate risks, and ultimately facilitate sensing technology adoption decision making. To achieve this, first a proposed governance framework is developed from the results of the triangulation, and then it was presented to the industry professionals for possible improvements and validation. The evaluation and validation process was designed to receive feedback from industry professionals to suggest improvements for the proposed framework and also to rate it on specific criteria for validation (see section 6.4). The result of evaluation and validation of the proposed governance framework was the validated governance framework to address objective 4 and achieve the aim of this research.

The first step in developing the proposed governance framework was to create its core structure to accommodate various aspects of technology adoption and important factors. In this regard, the core structure of the framework was generated from interview discussions on usual processes of new sensing technology adoption in a company. The core structure of the framework consists of three phases: proposal, evaluation and approval, and implementation. This indicates that the process of sensing technology adoption begins with a proposal on the applicability and suitability of a new sensing technology. Then the proposal goes through an evaluation. During evaluation of the proposal, some factors will promote and expedite the adoption; these are benefits and motivations towards implementing the new sensing technology. On the other hand, some factors will impede and challenge the adoption of the new sensing technology; these are the barriers. The proposal needs to be evaluated and approved by higher decision makers before implementation.

The second step in developing the framework was to assign categories of factors to relevant phases in the core structure. Factors that resulted from the triangulation were classified into six categories as specified in Table 6.3. Assuming that benefits provide motivations, the category for “benefits and motivations” will be referred to as “motivations” from here on. Thus, the six categories of factors in the proposed governance framework are: “motivations”, “barriers”, “considerations”, “people and organisation”, “whole of life cost” and “vendor/supplier”.

As illustrated in Figure 6.2, each of the six categories were assigned into the most relevant phase of sensing technology adoption. Motivations as well as barriers to technology adoption are usually well thought out and addressed in the proposal phase while the considerations are usually involved during both proposal and evaluation. In the main structure of the proposed governance framework, it is assumed the barriers constitute a major part of consideration, so they still affect the evaluation and approval phase. Factors related to people as well as justifications of the cost of the technology adoption are mostly considered during evaluation. Finally, when the new sensing technology is approved and goes through the implementation phase, suppliers or vendors can play important roles when assisting with a facile adoption of technology.

Figure 6.2 *The core structure and categories of factors associated with each phase of the proposed governance framework*



The third step of developing the proposed governance framework was to assign identified factors that affect sensing technology adoption to relevant categories in the proposed governance framework. This step followed categories in Table 6.3.

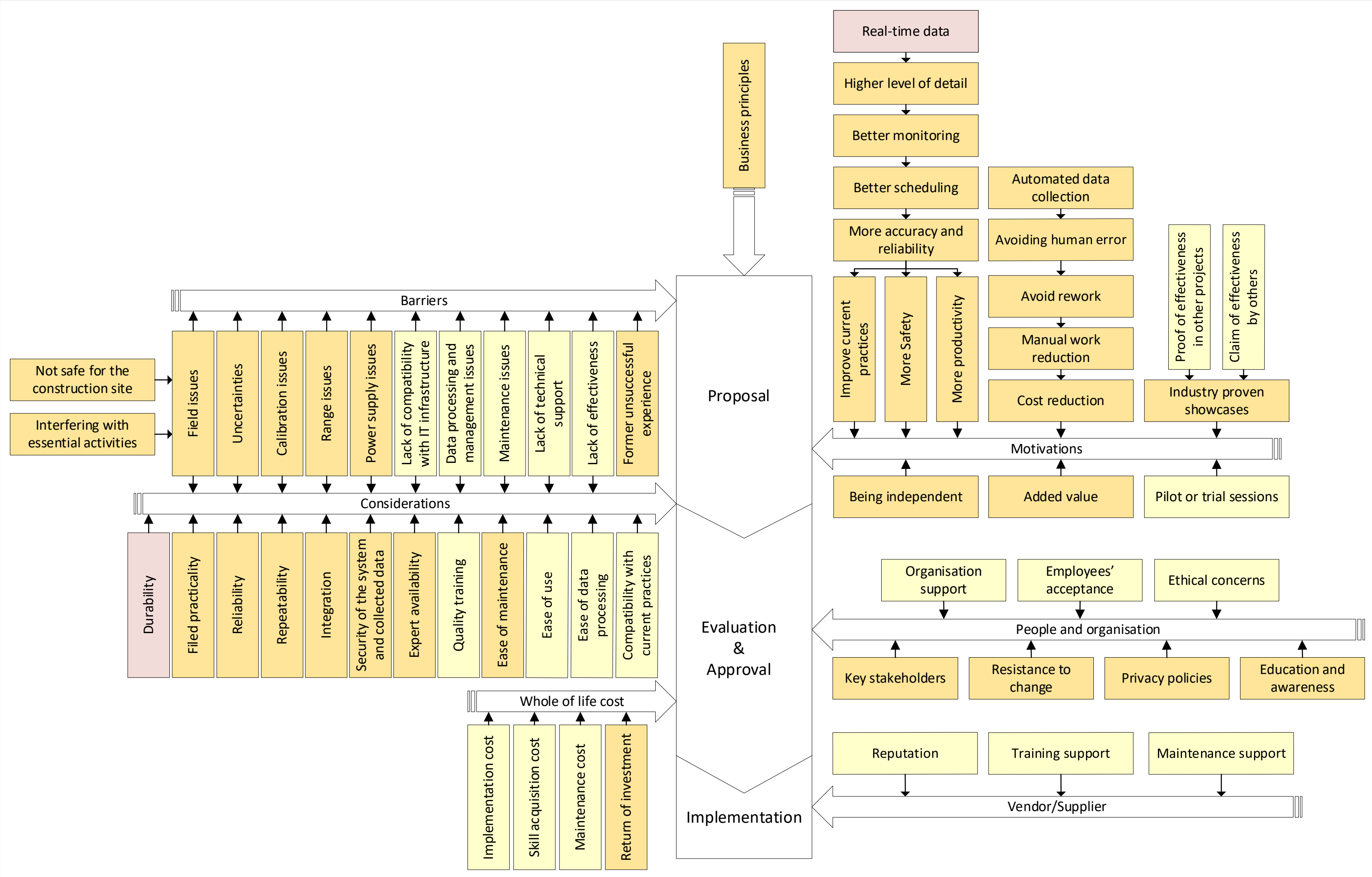
As illustrated in Figure 6.3, the 21 factors extracted from the survey analysis are presented in yellow boxes in the framework while the 37 factors extracted from qualitative analysis are shown in orange except for "vendor/supplier", which constitutes the category for vendors and suppliers. It is also worth mentioning that some of the factors from survey analysis (Table 6.1) were also discussed during the interview discussions but only represented once in the framework as survey input. "Real-time data" as a benefit, and the "durability" of sensors as a consideration, were not explicitly covered during the two approaches but added to the proposed governance framework in pink boxes, based on findings from the literature review, to make the framework more comprehensive.

As mentioned earlier and illustrated in Figure 6.3, the proposed governance framework consists of three sequential phases for sensing technology adoption: "proposal", "evaluation and approval", and "implementation". Different categories are associated with each stage, containing relevant factors that might affect sensing technology adoption and will need to be considered during decision making processes. While all factors in the proposed governance framework might not be applied to each and every case of sensing technology adoption, the framework is designed to comprehensively include all of the influential factors in the process of sensing technology adoption, regardless of the type of sensors.

"Business principles", as mentioned by highly experienced interviewees, is one major factor that works beyond and upon every other factor and category in the proposed governance framework since it governs most policies and actions around new sensing technology adoption from even before the proposal, through to evaluation and approval of the proposed technology adoption and during the implementation phase. Therefore, "business principles" was considered as a category of its own (see Table 6.3) and assigned to the proposed governance framework as an independent factor in the proposal phase. Business principles might vary between different companies and significantly affect the adoption of any innovation as they reflect philosophies and policies of the construction company. Only when business principles are open and welcoming to new opportunities, the process of sensing technology adoption begins with a proposal that is followed by the evaluation phase and, if approved, the implementation occurs. More discussion on three phases of sensing technology adoption in the proposed governance framework and categories of factors associated with each, is provided in section 6.3.1.

Figure 6.3 shows the proposed governance framework as the result of the triangulation.

Figure 6.3 *The proposed governance framework*



6.3.1 Discussion on phases and factors in the proposed governance framework

The three phases of sensing technology adoption along with the categories and factors associated with each phase are explained the following.

6.3.1.1 Proposal

The two major categories involved in the proposal phase of sensing technology adoption are “barriers” and “motivations”, as these two categories work in opposite directions in sensing technology adoption. Motivations promote new sensing technology while barriers deter from new innovations and need to be addressed and justified in a proposal. Most barriers also go into the category of “considerations”. Considerations affect both the proposal and evaluation phases as this category includes many factors that influence the adoption process from proposal to approval.

Motivations, in the proposed governance framework, range from perceived benefits to incentives towards new sensing technology adoption and to improvement of construction performance. In this category, some factors might be both benefits and incentives, whereas others are either of the two. For example, avoiding rework is both a benefit and an incentive, while an industry proven showcase is only an incentive. Whether motivations are a benefit or an incentive or both, they are treated equally in the proposed governance framework and only in the context of how each individual construction project/company/sensor, they might be treated differently.

Barriers mostly include technical issues either regarding the nature of the technology, construction site characteristics or access to the level of support required. Former unsuccessful experiences and uncertainties about the technology (if any) would also be two factors sabotaging the adoption of any new sensing technology and would need to be properly addressed in the proposal.

The category of considerations accommodates both barriers and suitable attributes that are vital to ensure the proposed sensing technology will serve the intended purpose. The considerations should justify and resolve the barriers while confirming -suitable characteristics of the proposed sensing technology. Although the considerations should mostly be addressed in the proposal, they still might affect the evaluation and approval of the proposed sensing technology.

6.3.1.2 Evaluation and Approval

Aside from the category of considerations, which works from the proposal stage all the way through to approval, factors related to “people and organisation” and the “whole of life cost” as shown in Figure 6.3 should be justified mainly during the evaluation phase before the approval. They also might have been considered earlier during the proposal, but is envisaged that their major influence would be during the evaluation of the proposed sensing technology. The reason behind this is the fact that determination of the whole of life cost would be only after the proposal and during the evaluation, although some rough estimates are necessary to the proposal stage. This is the same for the factors related to the people involved in the sensing technology implementation, whether key stakeholders or employees who will use the sensors. All the factors regarding the privacy policies and ethics also should be dealt with during this stage. Three factors from the survey analysis and four factors from the interviews are included in the category of people.

6.3.1.3 Implementation

The implementation phase comes only after the approval during which the interaction with the supplier or vendor is critical. The importance of the role of supplier was mentioned by a few on the interviewees although the interview questionnaire was not designed to specifically and directly inquire about it. No other aspect of the implementation phase was discussed unless an interviewee raised previously experienced issues and challenges, which were assigned to the category of considerations in order to eliminate those challenges and support sensing technology adoption with ease. This is because the interview questionnaire was designed to dominantly cover the factors that influence the adoption of sensing technologies rather than their implementation, although discussing some major factors in implementation was inevitable.

Accordingly, “vendor/supplier” is the only category assigned to the implementation phase by the proposed governance framework. Three factors of suppliers’ “reputation”, “training support” and “maintenance support” are associated with this category. Although they were also noted by the interviewees in the role of vendor/supplier, they only entered into the proposed governance framework as inputs from the survey results, to avoid repetition.

6.4 Evaluation and Validation of the Framework

The proposed governance framework as illustrated in Figure 6.3, was presented to selected construction professionals (as introduced in section 6.4.1) for being evaluated and validated. An online survey was designed for this purpose. The evaluation part of the survey was designed to identify possible missing factors in any of the categories and improve the proposed governance framework accordingly. The validation part of the survey was designed to investigate the comprehensiveness and applicability of the framework to assist construction stakeholders with easy sensing technology adoption. More details on the evaluation and validation of the proposed governance framework are provided in sections 6.4.2 and 6.4.3, respectively.

Appendix E presents the online survey questionnaire used for evaluation and validation of the proposed governance framework.

6.4.1 Profile of respondents

Purposive sampling was adopted for the evaluation and validation of the proposed governance framework in order to get the feedback from extensively experienced construction professionals who are well familiar with applications of sensing technologies to improve construction performance. An anonymous link to the online survey was sent to 12 selected construction professionals, asking for voluntary participation in an online survey. Selected construction professionals were highly experienced in construction and well knowledgeable about sensing technologies. These construction professionals were nominated from both samples of quantitative and qualitative data collection introduced earlier in Chapter 4 and Chapter 5. Of the 12 construction professionals that were invited to take part in the evaluation and validation survey, 10 completed the online survey, providing feedback for improving the proposed governance framework and also validating it. Table 6.4 gives more details on the profile of respondents to the evaluation and validation survey.

Table 6.4 *Profile of respondents to the evaluation and validation survey*

Number	Position	Expertise	Years of experience
1	Field engineer lead	Construction management Field engineering management	35
2	Project engineer lead	Industrial construction management Industrial scaffolding fabrication	40
3	Contracts manager	Mining construction Infrastructure construction	18
4	Construction manager	Project management Construction and fabrication	30
5	BIM manager	Building construction	10
6	Engineering manager	Transport infrastructure	16
7	Project manager	Mining construction	15
8	Construction manager	On-site and off-site construction management	11
9	Construction manager	Project management Construction management	20
10	Quality manager	Road construction	30

6.4.2 Improving the proposed governance framework

To investigate if the proposed governance framework needed improvement, the respondents were provided with Figure 6.3 and a brief description of it. Then, five questions were asked and the respondents were required to identify any missing factor in any of the categories of the proposed governance framework. Table 6.5 contains the five questions for framework evaluation.

Table 6.5 *Questions for evaluating the proposed governance framework*

Number	Question
Q1a	Is there any missing motivation to encourage construction stakeholders to adopt sensing technologies?
Q1b	Is there any missing barrier limiting the adoption of sensing technologies in construction?
Q1c	Is there any missing consideration for the decision making process of sensing technology adoption and implementation during construction?
Q1d	Is there any missing factor affecting the adoption of sensing technologies in construction which is related to people?
Q1e	Is there any missing factor related to the role of vendor or supplier in sensing technology adoption?

According to feedback received from respondents, missing factors from the framework were:

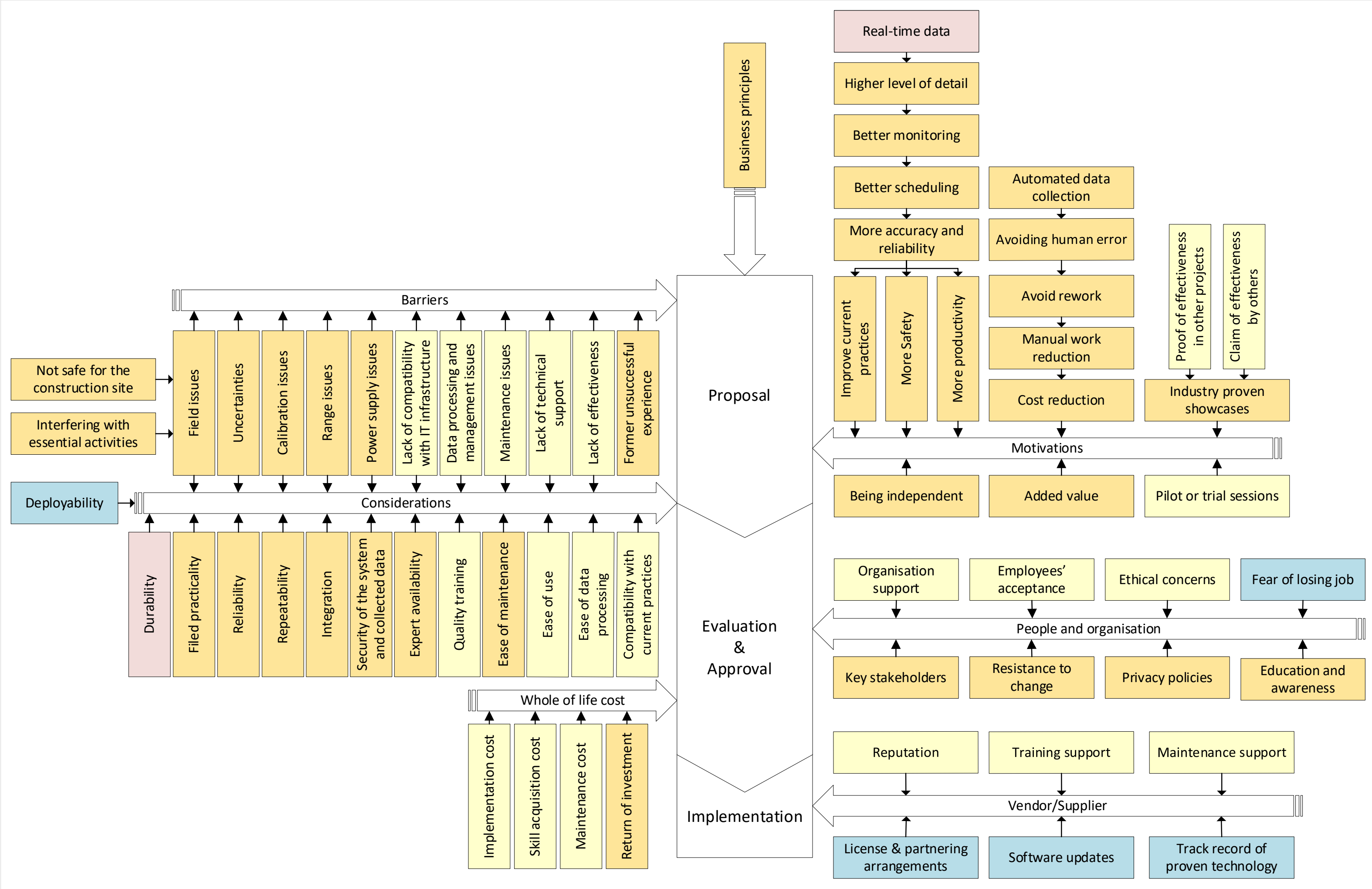
- “Fear of losing jobs” as a barrier related to people.
- “Deployability” of the technology as a consideration.
- “Licence and partnership arrangements” as a factor for vendor/supplier.
- “Software updates” as a factor for vendor/supplier.
- “Track records of proven technologies” as a requirement from vendor/supplier.

Among the five missing factors, a few were implied in other factors elsewhere inside the framework. For example, the ninth respondent mentioned that vendors or suppliers should provide “proven track records” of their innovative technologies. This element was added to the “vendor/supplier” category in the improved governance framework (see Figure 6.4), however it was previously implied by “industry proven showcases” in the motivations. Likewise, “deployability” could be intrinsically embedded in “field practicality” in the same category for consideration. This could be the same case with “fear of losing jobs” and “resistance to change”.

Of the five factors listed by the respondents during the evaluation of the proposed governance framework, three were related to the category of vendor/supplier. It is worth mentioning here that the role of vendor or supplier was not a primary objective of the interviews and hence not included in the interview questionnaire. The role of vendors or suppliers was discussed only briefly if the interviewee raised the matter. That could explain why three of the five missing factors noted by the evaluators of the framework relate to the same category, because the evaluators were prompted by the framework to consider the issue.

The five missing factors identified during the evaluation, were added to the proposed governance framework as shown in blue in Figure 6.4 to improve the proposed governance framework. The governance framework, as improved through the evaluation and presented in Figure 6.4, fully addresses objective 4 of this research, only if it is validated by industry professionals.

Figure 6.4 *The governance framework*



6.4.3 Validation of the governance framework

Validation of the governance framework was conducted to fulfil three criteria of completeness, clarity and helpfulness in the governance framework. The criteria are based on the ontology evaluation proposed by Visser and Bench-Capon (1998) to investigate epistemological adequacy (clarity, relevance and completeness), operationality and reusability. This concept has been used by many researchers for the validation of previous studies in the construction management research area (El-Diraby and Kashif 2005; Macarulla et al. 2013; Shou et al. 2019).

Validating the proposed governance framework was done through the same survey as for the evaluation. After evaluating the proposed governance framework, the respondents were asked to rate the completeness, clarity and helpfulness of the proposed governance framework. Keeping in mind that recently added factors after the improvement of the framework have changed neither the applicability nor the context of the framework, it is believed that these additional factors have only improved the comprehensiveness of the framework and in no way have jeopardised its validity. Therefore, as long as the proposed governance framework (which lacks five factors) is valid, the improved framework will be valid in the first place. As shown in Figure 6.4 , only five elements out of the total of sixty three were missing from the results of triangulation analysis and hence from the proposed governance framework which is less than 8%. This means that the triangulation contributed about 92% of the factors in the governance framework with the remaining 8% contributed as a result of the evaluation. Therefore, the proposed governance framework did not fundamentally change and was only improved by the evaluation and validation survey.

For the validation of the framework, seven questions were designed to address the three mentioned criteria. The first criterion was about the completeness of the framework, meaning the extent to which the framework was comprehensive regarding various factors related to sensing technology adoption. The second criterion was regarding the clarity of the governance framework, to see if the appearance of the framework and the flow of different factors was clear enough. This criterion also investigates if every factor was in the most appropriate category within the framework. The third and last criterion of validation was around helpfulness and reusability of the governance framework. It explored the extent to which the respondents believed the governance framework was capable of supporting a wider adoption of sensing technologies in construction.

Respondents were asked to rank each question from 1 to 5, where 1 was "strongly disagree", 2 was "disagree", 3 was "neither agree nor disagree", 4 was "agree" and 5 was "strongly agree". Table 6.6 contains all seven questions used for validating the governance framework.

Table 6.6 *Criteria and questions for validating the governance framework*

Criteria	Question
Completeness	Q1. To what extent do you agree that the framework covers all relevant factors for sensing technology adoption?
	Q2. To what extent do you agree that all the factors in the framework are relevant to sensing technology adoption?
Clarity	Q3. To what extent do you agree that the terminology used within the framework reflects the intuition of experts?
	Q4. To what extent do you agree that every factor within the framework is allocated to a proper stage of sensing technology adoption (proposal, approval and implementation)?
	Q5. To what extent do you agree that the concepts (factors) and their relations (classification) used within the framework are clear and explicit enough?
Helpfulness	Q6. To what extent do you agree that the framework is capable of assisting construction stakeholders and decision makers with a wider adoption of sensing technologies in construction?
	Q7. To what extent do you agree that the framework is usable and re-usable for the adoption of all types of sensing technologies in construction?

To validate each of the three criteria, the mean of the rankings in every question was determined and then a mean value for each criterion was considered to indicate the level of respondents' agreement in each criterion. Mean values equal to and under 3 are not acceptable, and mean values around 4 and above are considered as satisfactory, since the ranking of 4 was the rank of "agree", indicating that the respondents were agreeing that the proposed governance framework was satisfying required criteria for validation.

Table 6.7 shows that every individual question has a mean score of equal to or higher than 3.9 indicating the respondents positively supported the completeness, clarity and helpfulness of the governance framework.

Table 6.7 *Ranking for validation questions and associated mean in every question and each criterion*

Criterion	Question	Mean: For question	Mean: For criterion
Completeness	Q1. To what extent do you agree that the framework covers all relevant factors for sensing technology adoption?	4.20	4.25
	Q2. To what extent do you agree that all the factors in the framework are relevant to sensing technology adoption?	4.30	
Clarity	Q3. To what extent do you agree that the terminology used within the framework reflects the intuition of experts?	3.90	3.97
	Q4. To what extent do you agree that every factor within the framework is allocated to a proper stage of sensing technology adoption (proposal, approval and implementation)?	3.90	
	Q5. To what extent do you agree that the concepts (factors) and their relations (classification) used within the framework are clear and explicit enough?	4.10	
Helpfulness	Q6. To what extent do you agree that the framework is capable of assisting construction stakeholders and decision makers with a wider adoption of sensing technologies in construction?	4.20	4.15
	Q7. To what extent do you agree that the framework is usable and re-usable for the adoption of all types of sensing technologies in construction?	4.10	

The criterion for completeness has a mean score of 4.25, a high level of agreement on the completeness of the governance framework. The mean scores for questions 1 and 2 indicate the respondents positively support the view that the framework covered major factors in sensing technology adoption, and that all factors used in the framework were relevant to the intended context. To conclude, since the proposed governance framework is rated to satisfy an acceptable level of comprehensiveness, the governance framework improved by the evaluation (see Figure 6.4) is more comprehensive since containing the five extra factors noted in the evaluation.

The clarity of the framework has a mean score of 3.97, which is quite close to the score of 4. The mean scores for questions 3 and 4 reflect an acceptable level of agreement on the terminology used in the framework and the accurate allocation of factors to different stages of sensing technology adoption. The mean score of question 5 (4.1) demonstrates a satisfactory level of consensus that the framework has a clear and explicit flow. Although there is still room for improving the terminology and relevance of factors in the governance framework, its overall clarity is acceptable, as the overall mean score of 3.97 is close to the score of agreement (score 4). As a result, the proposed governance framework is considered to be clear and explicit, as is the improved governance framework (see Figure 6.4).

With regard to helpfulness and reusability, the mean score was 4.15. The mean scores for questions 6 and 7 indicate the respondents were confident that the governance framework can help with the adoption of sensing technologies during construction and that it is useful and re-usable for various types of sensing technologies. Again, when the proposed governance framework has been validated as helpful, so can the improved governance framework (see Figure 6.4) be reliably regarded as helpful for sensing technology adoption in construction.

With all three criteria for the validation satisfied, it is concluded that the proposed governance framework (Figure 6.3) is validated in its completeness, clarity and helpfulness, as is the governance framework (Figure 6.4) since it is basically the same framework, but more comprehensive than the proposed governance framework. Therefore, the objective 4 of this research is met and completed since the governance framework (Figure 6.4) is acknowledged to be valid.

6.5 Supplementary Frameworks

After ensuring that the governance framework was valid and accommodated all major factors for sensing technology adoption in construction, two supplementary frameworks were developed. The purpose of these supplementary frameworks was to focus on two specific aspects of sensing technology adoption: motivations towards new sensing technology adoption and assessing whether a new sensing technology is fit for purpose or not.

Another reason for developing these secondary frameworks is a comment from one of the respondents during the evaluation of the governance framework. A construction manager with over 20 years of experience in infrastructure projects, the respondent mentioned the framework was very detailed, and it might be helpful to create specific frameworks to address general questions and concerns about new technology implementation such as: “Does it save money or add value?” and “Can someone prove that it works?”.

It is assumed that since these two supplementary frameworks are extracted from the validated governance framework, there is no need to evaluate them again. Besides, the following two frameworks will complement sensing technology adoption in construction and exceed the primary intention of this research.

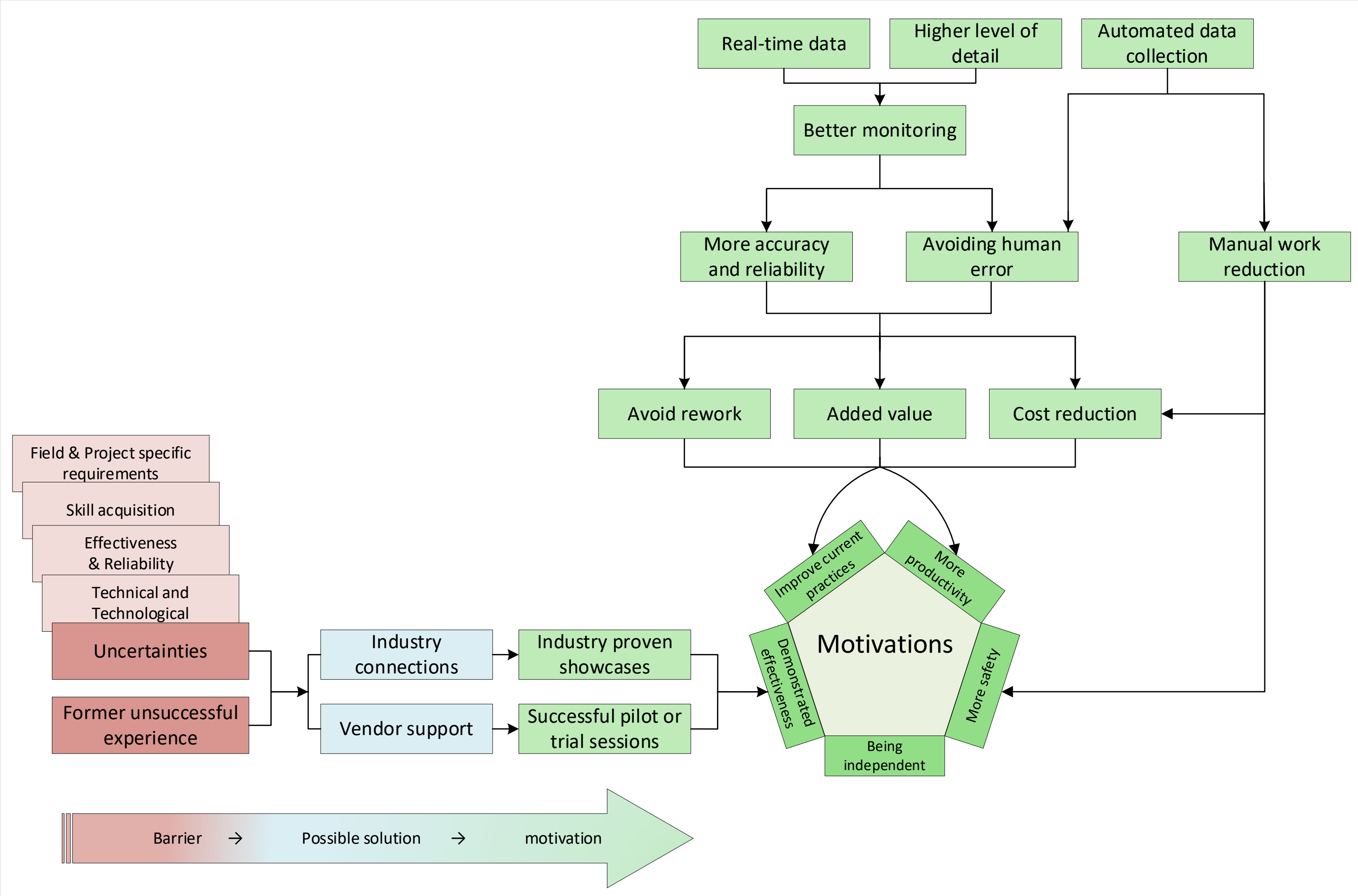
6.5.1 Motivating framework

A motivating framework has been developed as a secondary outcome of triangulation using the same factors from the governance framework. The motivating framework accommodates for major motivations extracted from the governance framework towards a wider adoption of sensing technologies in construction and also highlighting a figurative transformation of barriers into motivations.

As illustrated in Figure 6.5, five core motivations are recognised that might be either a result of other motivations or benefits regarding the application of a suitable type of sensing technology in construction (improved current practices, more productivity and more safety), a transformation of various barriers through possible solution (demonstrated effectiveness), or even a free motivation (being independent).

Figure 6.5 demonstrates how various benefits result in relative motivations. For example, “real-time” data combined with “higher level of detail” are the benefits of adopting a suitable type of sensing technology which can result in “better monitoring” through “more accuracy and reliability” as well as “avoiding human error”, which leads to “avoid rework”, “added value” and “cost reduction”. It also represents a possible scenario to transform some barriers into motivations. For example, barriers of “former unsuccessful experience” or various “uncertainties” regarding a new sensing technology might be converted into a motivation via a suitable solution such as “industry connections” or “vendor support”.

Figure 6.5 *Motivating framework*



6.5.2 Appraisal framework

The second supplementary framework (Figure 6.6) is an appraisal framework for assessing substantial considerations that concern whether or not a new sensing technology is fit for the intended purpose in construction. The appraisal framework tries to point out major concerns that are critical to dealing with uncertainties. This supplementary framework helps to minimise possible risks associated with introducing a new sensing technology into construction activities.

This framework (Figure 6.6) consists of four streams of questions to be asked during the proposal and evaluation of a new sensing technology. Addressing the questions facilitates the process of adopting sensing technology because confidence in the fitness of proposed sensing technology is increased, and the chance of future risks and complications associated with the adoption of the new sensing technology is reduced.

Figure 6.6 *Appraisal framework*

6.6 Summary

In this chapter, triangulation addressed the fourth objective of this research by integrating all results from objective 3. The aim of the triangulation was to develop a governance framework that included as many factors as possible, factors which might influence the adoption of any sensing technology in construction. Various factors from both quantitative and qualitative methods of obtaining data to achieve objective 3 were reviewed, combined and compared against the findings of the literature review for possible missing factors. Consequently, all factors emerging from the triangulation were categorised and assigned to relevant places in the governance framework.

As a result, 21 major factors from the quantitative analysis and 37 factors from the qualitative analysis, and two from the literature review, were integrated to build a proposed governance framework to assist with the adoption of sensing technologies in construction. This framework was then presented for evaluation and validation by industry professionals highly experienced in construction and proficient in using sensing technologies. The evaluation resulted in improving the proposed governance framework through five additional factors noted by the construction professionals. The proposed governance framework was also validated on the basis of its comprehensiveness, clarity and helpfulness. Since the evaluation of the proposed governance framework improved it only slightly, and it was validated for the noted criteria, the governance framework (as illustrated in Figure 6.4) is also acknowledged to be valid on the same criteria and therefore addressed objective 4.

Using the same factors in the governance framework, two secondary frameworks were developed for more specific purposes, being the motivating framework and the appraisal framework. The motivating framework emphasises benefits and opportunities for transforming barriers into motivations to adopt sensing technologies. The appraisal framework consists of critical questions that need to be addressed before introducing any new sensing technology into construction practices. The appraisal framework facilitates future risk minimisation associated with implementation of sensing technologies for on-site or off-site construction management.

Chapter Seven

7

Research Findings and Discussion

7.1 Introduction

The aim of this chapter is to summarise the findings and discuss different aspects of sensing technology adoption established through qualitative and quantitative methods in this present research study. First, a summary of key findings is given for each of the four research objectives. Then, different aspects of sensing technology adoption are discussed and compared with the findings of previous studies in similar areas.

7.2 Research Findings

This section summarises the research findings for each of the four research objectives in order to draw conclusions about the current status of sensing technologies and factors that are believed to affect the adoption of sensors in the construction industry. Evidence is provided regarding the capabilities of employed research methods to address research objectives. The findings explore the current status of sensing technologies in construction along with barriers and motivations towards a wider use of such innovations during construction practices.

7.2.1 Research findings for objective 1

Research objective 1 was "to obtain an in-depth understanding of existing and applicability of sensing technologies with potential benefits for construction performance". A literature review identified types of sensing technologies and their applications to improve construction safety, quality or productivity. Table 7.1 summarises the findings from objective 1.

7.2.2 Research findings for objective 2

Research objective 2 was "to identify in-use sensing technologies during the construction phase in actual projects and acquire an estimate of their prevalence in order to collate against findings from the literature". The data for the second objective was obtained through an online survey inquiring about how frequently selected types of sensing technologies are being used during construction. Selected sensing technologies consist of GPS, RFID, UWB, FOS, pressure sensing, temperature sensing, visual sensing and 3D scanning.

The findings for this objective were achieved through a descriptive analysis of the collected data on the current status of selected technologies in three different sectors of construction industry, namely building, infrastructure and industrial construction.

Chapter 4, section 4.4 supports a claim that the uptake of sensing technologies in construction has been slow.

GPS

GPS technology in construction is among the most popular sensing technologies in the construction industry. Only 20% of respondents working in building construction acknowledged they use GPS on a daily basis in their projects, while 16% were not using it at all. Daily use of GPS increases to 31% and 38% in industrial and infrastructure construction, respectively. Only respondents in industrial construction confirmed that they use GPS in their projects at least at some level, while 9% of respondents from infrastructure construction said they do not use GPS in their projects at all. A cross-sector comparison demonstrates that GPS has acquired the highest implementation level in industrial construction projects and the lowest adoption rate among building companies.

RFID

Regarding the current status of RFID technology, a low rate of implementation was observed where 75% of respondents in building construction, 50% of respondents from industrial construction and 47% of respondents from infrastructure construction were not using RFID technology in their projects at all. Only 7% of respondents in building construction and 6% of respondents in infrastructure and industrial construction were using RFID technology in their projects on a daily basis. This indicates a low adoption of RFID technology in construction compared to its capabilities to improve construction performance. A cross-sector comparison showed more RFID implementation in infrastructure and industrial construction projects than in building construction projects.

UWB

The use of UWB technology is even less common than RFID in construction projects across all three sectors. In building, infrastructure and industrial construction, 82%, 77% and 58% of respondents respectively acknowledged they do not use UWB at all. Only 3% of respondents in industrial construction projects use UWB on a daily basis while this rate is zero in the other two sectors. UWB was recognised as the least commonly adopted and the least frequently used sensing technology during construction among the selected technologies.

FOS

FOS has been more widely used among respondents from the industrial sector in construction industry rather than those in building and infrastructure construction. Of the respondents from the industrial construction sector, 70% use FOS at least at some level in their projects, either on a daily basis (11%), frequently from time to time (22%), only occasionally (22%) and very rarely (15%). Almost the same rate of respondents from building and infrastructure construction do not use FOS in their construction projects at all (72% in building and 69% in infrastructure construction).

Pressure sensing

Pressure sensing, in a cross-sector comparison, is more used in industrial construction rather that the two other sectors. 66% and 69% of respondents working on building and infrastructure construction projects do not use any pressure sensing at all while this reduces to 28% in industrial construction projects. None of the respondents from building construction and only 3% of respondents from infrastructure construction were using pressure sensors on a daily basis, while 11% of respondents from the industrial construction were using them on a daily basis. Likewise, only 3% and 12% of respondents from building and infrastructure construction acknowledged that they use pressure sensors in their projects frequently from time to time, while this rate surges to 28% in industrial construction projects.

Temperature sensing

A higher level of implementation was observed in the current status of temperature sensors which is envisaged to be associated with the fact that temperature sensors are sometimes a requirement for environmental monitoring of construction projects. A cross-sector comparison again showed that the industrial construction is the lead sector in the uptake of temperature sensing. Temperature sensing were acknowledged to be used on a daily basis in industrial construction projects by 33% of respondents, in infrastructure construction by 15% of respondents and in building construction by 13% of respondents. However, noticeable percentages of those respondents who admitted that they do not use temperature sensors in their projects (49% in building, 41% in infrastructure and 28% in industrial construction projects) indicate that temperature sensors also have been overlooked in the construction industry.

Visual sensing

Visual sensing (including visual recordings) is more popular than other types of technologies in all three sectors while industrial construction projects are still more dominant in its uptake. 50% of respondents form industrial sector rated their use of visual sensing technologies as being on a daily basis. Daily use of visual sensing in building and infrastructure construction is 25% and 19% respectively. On the other hand, 25% of respondents from the building sector, 17% from infrastructure sector and 14% from industrial sector admitted that they do not use any kind of visual sensing (or recording) in their construction projects.

3D scanning

A cross-sector comparison on the current status of 3D scanning showed that industrial construction projects are leading the way towards 3D scanning technology adoption. 22% of respondents from industrial sector said they use 3D scanners on a daily basis, while this rate drops to 3% in building and infrastructure construction. On the other hand, only 14% of industrial construction projects are not involved in using 3D scanning technology at all while 44% of building and 49% of infrastructure construction projects are not involved in ant 3D scanning at all.

A comparison between the first two objectives of this research shows a clear gap between the capabilities of various types of sensing technologies and associated level of implementation they have acquired in the construction industry. Especially in the case of RFID and UWB, the current status of implementation in actual construction projects is far behind reported opportunities in which these technologies are capable of making a change. The literature is abundant with research on how RFID or UWB can impact construction safety and productivity, but these two are not properly in use in construction projects. The same, more or less, goes to the rest of sensing technologies. Besides, some other more contemporary technologies like wearable sensors are not still adopted by Australian construction companies and so are not included in the current status of sensing technologies in construction in this research.

Table 7.1 *Most noted sensing technologies and their application to improve construction performance*

Technology	Applications in construction
Location-based sensing	
GPS	Safety improvement: – Unsafe proximity detection – Situational awareness of on-site workers – Equipment localisation, tracking and monitoring – Personnel position tracking Productivity enhancement: – Resource localisation, tracking and monitoring – Real-time material tracking – Equipment navigation systems Automation: – Real-time activity recognition of construction equipment to correct the operation if necessary
RFID	Safety improvement: – PPE detection and monitoring – Proximity detection alert systems to avoid accidents – Access controls to restricted areas – Storage of safety information Productivity enhancement: – Identification and real-time tracking of construction materials – Indoor construction localisation and tracking of construction resources, equipment and workers – Asset management and supply network visibility – Time and schedule management – Automatically updating progress reports Waste management

Technology	Applications in construction
UWB	Safety improvement: – Dynamic hazard zones identification – Collision avoidance – Situational awareness of construction workers and equipment operators Productivity enhancement: – Resource and material tracking in indoor construction sites, harsh environment and indoor obstructed sites – Location tracking of staff in productivity measurement – Real-time 3D resource localisation
Vision-based sensing	
3D scanners	Safety improvement: – Situational awareness of equipment operators Productivity enhancement: – Automated progress tracking – Construction activities workflow monitoring Quality performance: – Acquisition of 3D images and geometries of buildings and built environments – Simulation of virtual construction sites for training purposes
Kinect	Safety improvement: – Detection of workers’ posture – Motion capture and action recognition of workers

Technology	Applications in construction
2D and 3D cameras	Safety improvement: – Monitoring safety of personnel on site – Assist with tower crane blind lifts – Communication between project network and workfront Productivity enhancement: – Tracking construction resources – Construction workflow monitoring to identify inefficient processes OHS management: – Monitoring use of PPEs on site – Workers' movement prediction and unsafe behaviour identification
WSN	
FOS	Safety improvement: – Structural safety monitoring through measuring strains deformations and cracks in tunnel segments and concrete structures OHS management: – Environmental monitoring in hostile surroundings such as real-time temperature monitoring of frozen soil Quality control of: – Asphalt compaction – Concrete curing process
Pressure sensors	Load measurement in safety monitoring of roads, bridges, tunnels, and buildings, etc.
Displacement sensors	Structural health monitoring – Inclination and subsidence monitoring

Technology	Applications in construction
Temperature sensor	Safety improvement: – Environmental monitoring Quality controls: – Curing and shrinkage crack monitoring of mass concrete – Environmental monitoring
Wearable sensors	
Motion sensors	Improving safety performance and OHS management by: – Detecting awkward postures to prevent fatalities and accidents – Detecting gait abnormalities and body posture sensing for fall risk assessments – Monitoring proper use of helmets – Identify potential work-related ergonomic risks through body posture sensing
Integration of various sensors in PPEs (physiological, motion, environmental, RTLS, cameras, etc.)	OHS management: – Wellbeing programs – Early warning systems to safeguard wellbeing, – Measuring psychological status to reduce unsafe behaviours – Location tracking and proximity detection – Monitoring proper use of PPEs Environmental sensing: – Detecting chemicals, gases and excessive respirable dust

7.2.3 Research findings for objective 3

Research objective 3 was "to understand construction stakeholders' perceptions of sensing technologies, affiliated effectiveness, benefits and barriers, as well as major factors influencing sensing technology adoption in construction". This objective has been achieved through an extensive literature review followed by concurrent quantitative and qualitative methods. Findings from this objective formed the backbone to the fourth objective and research aim.

Reviewing construction stakeholders' perceptions of sensing technologies as reported in the literature resulted in having two broad categories of factors which affect the adoption of sensing technologies in construction. They are "benefits and motivations" and "barriers" towards adopting sensing technologies in construction. Aside from the perception of key stakeholders, construction workers' acceptance of sensing technologies was also reviewed in the literature. Key findings for objective 3 are summarised as follows.

7.2.3.1 Findings from literature review

The literature shows that the construction industry has been reluctant to adopt digital technologies and innovations (Love and Irani 2004; Stewart, Mohamed and Marosszeky 2004; Sepasgozar and Bernold 2013b; Heller and Orthmann 2014; Aghimien et al. 2018). An extensive literature review identified factors affecting the adoption of digital technologies in construction. The findings from that review established a foundation to construct the structures to undertake qualitative and quantitative methods of data collection to understand which factors affect the adoption of sensing technologies in particular.

Important factors influencing the adoption of various types of digital technologies were extracted from the literature. These factors formed the backbone of online survey for quantitative data as well as interview questionnaire for qualitative approach to further investigate the construction stakeholders' perceptions of sensing technologies. Such factors are classified and summarised as follows.

Benefits and motivation

Being aware about the benefits and capabilities of ICT as well as being exposed to relevant devices contributes to a more effective and efficient technology adoption in construction site management (Usman and Said 2012; Hong et al. 2016). Through the literature review the researcher discovered the extent to which construction stakeholders are aware of the benefits and competencies of different types of digital technologies (mostly IT and communication technologies) in their field of construction. The most noted benefits and privileges of such technologies are summarised in Table 7.2.

Barriers

According to the literature, most barriers to digital technology adoption in construction are either related to cost, process, technology or people (Sardroud 2014; Odubiyi, Aigbavboa and Thwala 2019). Barriers to the adoption of digital technologies in construction mentioned in the literature are summarised in Table 7.2 regardless of their classifications.

Employees' acceptance

Perceived usefulness and perceived ease of use have been two important measures in technology acceptance model introduced by Davis (1985), but more have been reported to be critical when it comes to sensing technologies especially wearable sensors. Being able to promote occupational safety through identifying health risks has been reported to be a major motivation towards accepting wearable sensors (Häikiö et al. 2020; Jacobs et al. 2019) while privacy, security and confidentiality were among the biggest concerns (Choi, Hwang and Lee 2017; Schall, Sesek and Cavuoto 2018; Häikiö et al. 2020; Mettler and Wulf 2018; Jacobs et al. 2019).

Table 7.2 *Benefits of and barriers to digital technology adoption in construction according to the literature*

Benefits
Cost reduction
Time saving and improved productivity
Improved performance
Error minimisation
Increased information
Better monitoring
Better facilities management
Improved leadership and decision support systems
Reduced risk of injury and illness
Increase employees' wellness and satisfaction
Better document quality
Improved quality of construction project delivery
Process improvement
Barriers
Cost of implementation
Cost of training and employing professionals
Maintenance cost
Operating cost
Uncertain cost benefit relation
Lack of interest and resistance to change
Lack of understanding or sufficient information
Lack of well-trained staff or adequate training
Employees' compliance
Company culture
Restrictive regulation or lack of government support
Legal and ethical concerns
Technology immaturity
Operational difficulties
Lack of proper IT infrastructure or software compatibility
Data management issues
Power supply issues
Site-related issues
Change in the process
Good manufacturing practice requirements

7.2.3.2 Findings from quantitative analysis

PLS-SEM on data collected through the online survey on the importance of various factors showed that the factors presented in Table 7.3a significantly affect the adoption of sensing technologies in construction, and nine hypotheses describe the relationships between different groups of factors. Research hypotheses supported by PLS-SEM are also presented in Table 7.3b.

Table 7.3a *Findings from quantitative data analysis – influential factors*

Affordability
Implementation cost
Maintenance cost
Skill acquisition cost
Technical constraints
Effectiveness issues
Not adaptable with IT infrastructure
Hard to get quality technical support
Hard to manage and analyse too much collected data
Hard to get quality training
Hard to maintain
Organisational Culture
Organisational support and approval
Acceptance between employees
Ethical concerns and privacy of employees
Supplier Characteristics
Reputation of the supplier
Quality training support from the supplier
Quality support from the supplier during maintenance
User-friendliness
Easiness of handling data
Simplicity of use
Compatibility with current systems and activities
Demonstrated Effectiveness
Proof of effectiveness from other industry parties
Proof of effectiveness on trial sessions
Proof of effectiveness in similar projects

Table 7.3b *Findings from quantitative data analysis – Research Hypotheses supported by PLS-SEM*

Number	Hypothesis
1	Supplier characteristics positively affect organisational culture
2	Supplier characteristics positively affect affordability
3	Supplier characteristics positively affect user-friendliness
4	Supplier characteristics positively affect demonstrated effectiveness
5	Demonstrated effectiveness positively affects user-friendliness
6	Demonstrated effectiveness positively affects technical constraints
7	Organisational culture positively affects technical constraints
8	Technical constraints positively affect user-friendliness
9	User-friendliness positively affects affordability

7.2.3.3 Findings from qualitative analysis

Qualitative analysis of interview transcriptions identified construction stakeholders' perceptions of sensing technologies including associated benefits from using them, motivations towards adopting them, barriers holding back from trying them, and considerations to take into account before adopting them. A summary of the coding and thematic analysis of the interviews is presented in Table 7.4.

Table 7.4 *Findings from qualitative data analysis*

Theme	Node –Child node
Factors affecting the adoption	
Benefits	More safety
	Higher productivity
	Better monitoring
	More accuracy
	Manual work reduction
	Less human error
	Cost Reduction
	Higher level of detail
	Higher reliability
Barriers	Technical issues: – Field issues – Range issues – Power supply – Data processing – Maintenance – Calibration – IT infrastructure – Interference with essential activities
	Financial constraints: – Implementation cost – Training cost – Maintenance cost
	Uncertainties
	Ethical concerns
	Skill acquisition: – Training staff – Employing experts
	Former unsuccessful experience
Suitability	Effective: – Reliable – Repeatable
	User-friendly: – Simple to use – Simple to maintain – Simple to process data
	Safe to the construction site
	Proper training
	Vendor support

Theme	Node –Child node
Motivations	Improved productivity
	Improved safety
	Better scheduling
	Added value
	Improved current practices
	Being independent
	Successful trial
	Successful showcases
People’s attitude	Business principles
	Key stakeholders
	Employees
Potential betterments	
	Practicality and use: – Extended use – Integration – Automation – Better power supply – More security
	Knowledge: – More awareness – Understanding data
	Lower cost
External collaboration	
	Looking for new technologies: – Word of mouth – Vendor – Desktop research – Subscription to newsletters – Technology department – Trade shows – Academic research
	Supportive parties: – Sensor end-users – Government and ministerial authorities – Sensor developers and suppliers – Academia and researchers – Clients
	Vendor/supplier
	Trade unions

7.2.4 Research findings for objective 4

Research objective 4 was aligned to the research aim: to develop a framework assisting with the process of new sensing technology adoption into the construction practices, highlighting motivations towards a wider adoption along with barriers and concerns that need to be addressed. The objective has been addressed using triangulation analysis of the results from the quantitative and qualitative analysis and findings of the literature review. The triangulation made possible a governance framework to be developed.

In order to identify as many important factors influencing the adoption of sensing technologies as possible, 21 factors were obtained from quantitative data, 37 from from qualitative data, and two from the literature. The governance framework was evaluated by selected industry professionals and found to be valid regarding its comprehensiveness, clarity and usability. The framework was improved and made more comprehensive with suggestions from a few evaluators, while its validity was not affected. The governance framework was found to be comprehensive, clear and helpful for sensing technology adoption in construction.

Aside from the governance framework, two supplementary frameworks were developed. They focused on specific aspects of sensing technology adoption, extracted from the governance framework.

The **motivating framework** highlighted the benefits of sensing technologies in construction that lead to motivations for adoption. It also figuratively demonstrated how certain types of constraints could potentially turn into motivations.

The **appraisal framework** concentrated on critical concerns that need to be considered and addressedwhen assessing the suitability of a particular sensing technology to improve construction performance.

7.3 Research Discussion

The contribution and results of the current research are summarised and represented in the governance framework. The governance framework, as illustrated in Figure 6.4, is developed as a reference for various factors that might affect the adoption process of a new sensing technology. Contrary to some previously developed frameworks such as the ADC implementation framework (Sardroud 2014), the governance framework developed in this present research is a comprehensive framework embracing detailed factors that might in any way—positive or negative—affect the adoption of sensing technologies in construction projects, regardless of the type of the technology.

The governance framework is partially covered and therefore supported by frameworks from previous research studies. For example, the ADC implementation framework (Sardroud 2014) has shown that people and organisational levels of ADC technology implementation should be considered at the same time for specific ADC technology implementation. This current research has noted the same concept in the governance framework during the evaluation and approval phase of a new sensing technology and before its implementation. Likewise, Sepasgozar, Loosemore, and Davis (2016) proposed that a construction company, as a customer of new technology, takes the following actions for technology adoption: investigation, adoption decision, and implementation and each of these three phases involve various stages. The exact sequence is proposed in the core structure of the governance framework: proposal of the appropriate sensing technology (similar to the investigate phase), evaluation and approval (similar to adoption decision) and the implementation phase.

The governance framework, as mentioned before, embraces a wide range of factors that might promote or deter the adoption of new sensing technologies. Although some factors in this framework might be more important or more likely than others, and were extracted from different resources (quantitative analysis, qualitative analysis or literature review), they are all treated similarly inside the governance framework. This is because the governance framework only indicates possible factors that might (or might not) affect the adoption of a specific sensing technology, but the likelihood of their possibility might be different for different sensing technologies or in different circumstances. The other matter about the governance framework is that the factors are allocated to the most relevant category and phase of sensing technology adoption, and some might still be applicable in other categories or phases. Moreover, this framework comprises common and unique factors to sensing technology adoption in the construction industry.

In this section, different aspects of the governance framework are compared with similar studies in the literature. The following classifications are defined for the purpose of the discussion: “common motivations” and “common barriers” that mutually influence sensing technology adoption and the adoption of other technologies, and “unique motivations” and “unique barriers” that are mostly identified in the case of sensing technology adoption.

7.3.1 Common motivations related to new digital technology adoption

The qualitative analysis of interviews revealed interviewees were indeed aware of the benefits of sensing technologies to improve construction performance. The following benefits and motivations extracted from the governance framework are those common to sensing technologies and other types of similar innovations. It should be noted that, despite awareness of the noted benefits, these technologies are not widely used on construction sites because of various barriers identified in this research. The literature supports this claim in the case of data capturing technologies (Alizadehsalehi and Yitmen 2018).

Improved performance

One of the most noted benefits of using sensing technologies was found to be achievement of a higher level of safety performance in construction. Since the construction industry is quite labour-intensive, prone to work-related injuries and fatalities as well as disease-causing hazards (Safe Work Australia February 2015), the interviewees declared they are willing to use sensing technologies in order to improve construction safety performance through avoiding hazards and promoting OHS. This finding is in accordance with the literature on using IoT for construction safety monitoring (Häikiö et al. 2020), and a willingness to use wearable sensors to improve workplace safety and reduce the risk of injury and illness (Schall, Sesek and Cavuoto 2018; Jacobs et al. 2019). The literature about possible applications for different types of sensing technologies supports the ability of these technologies to improve construction safety performance, including the application of sensor-based technologies to improve construction safety management (Zhang, Cao and Zhao 2017), IoT real-time early warning systems to prevent accidents and improve safety (Ding et al. 2013; Kanan, Elhassan and Bensalem 2018), and RTLS for labour tracking and for monitoring to prevent accidents (Kwang-Pyo et al. 2014), etc.

Improving construction productivity is another benefit which motivates construction stakeholders to implement sensing technologies. Improved productivity has also been reported as both a benefit and a motivation to technology adoption in construction in research in similar areas such as the adoption of ICT (Akinbile and Oni 2016) and digitalisation (Aghimien et al. 2018), data capturing technologies in automated construction progress control management (Alizadehsalehi and Yitmen 2018), and wearable sensors to improve employees' productivity (Schall, Sesek and Cavuoto 2018).

Improved current practices including better monitoring and better scheduling were mentioned by the interviewees as motivations to adopt sensing technologies. This is in accordance with the literature that reported process improvement as a top motivation in using data mining in construction (Ahmed et al. 2018). In other instances, it is reported the construction industry can achieve better document quality by adopting more digitalisation (Aghimien et al. 2018), and web-based project management can marginally enhance effective monitoring and control during project delivery (Doloi 2014).

Another benefit of sensing technology implementation that most of the interviewees agreed on was having increased information and access to a higher level of detail, which positively impacts various aspects of construction management and decision making. This claim is supported by previous studies. For example, enriched knowledge was reported to be among the top benefits of using ICT in construction industry (Akinbile and Oni 2016). Likewise, an increased amount of information by using WSN in construction can lead to better facilities management and levels of monitoring and control (Heller and Orthmann 2014). Remote decision making is also facilitated by remote visual inspections with advanced field data capturing technologies (Alizadehsalehi and Yitmen 2018).

Vendor/supplier support

Vendor companies or suppliers are involved in the implementation process (Sepasgozar et al. 2018) and play an important role in the adoption of sensing technologies in construction in different ways, such as providing after sales support (Sepasgozar and Loosemore 2017; Sepasgozar et al. 2018), proper training on technology utilisation (Sepasgozaar, Shirowzhan and Wang 2017) and technical support during maintenance (Sepasgozaar, Shirowzhan and Wang 2017; Sepasgozar et al. 2018). Other important factors that can facilitate technology adoption include the reputation of vendors (Goodrum et al. 2011; Sepasgozar and Davis 2018), vendor responsiveness to spare parts (Sepasgozar et al. 2018) and good manufacturing practices (Schall, Sesek and Cavuoto 2018),

In addition, the PLS-SEM path modelling showed supplier characteristics had a critical role by positively affecting organisational culture, technology affordability, technology user friendliness and demonstrated effectiveness (hypotheses 1 to 4). This emphasised the role of vendors or suppliers in sensing technology adoption which agrees with previous studies investigating the role of vendors and suppliers in technology adoption (Sepasgozar 2015; Sepasgozar and Davis 2018). Vendors and suppliers can facilitate technology adoption by providing relevant information and supportive activities such as demonstrating the effectiveness of the innovative technology through trials or providing access to referees (Sepasgozar and Davis 2014).

User friendliness

The governance framework suggests a new sensing technology has a greater chance of adoption if it is user-friendly. User friendliness in a new sensing technology means the ease of using the proposed technology as perceived by end users. User friendliness in a new sensing technology is demonstrated in the form of ease of use, ease of data processing, ease of maintenance, and compatibility with current devices and IT infrastructure in the governance framework. Perceived ease of use was introduced by Davis (1985) to define the acceptance of an innovation and was reported to have a prominent role in the adoption of that innovation (Davis 1989). Perceived ease of use has been used by many researchers to study attitudes towards new technologies in the construction industry (Adriaanse, Voordijk and Dewulf 2010; Goodrum et al. 2011; Son et al. 2012; Lee, Yu and Jeong 2015; Sepasgozaar, Shirowzhan and Wang 2017; Ahn et al. 2019; Elshafey et al. 2020). The importance of user friendliness in a new proposed sensing technology is found in previous findings in the literature that ease of operation and ease of maintenance would contribute to easy implementation of a new technology in construction projects such as BIM (Hong et al. 2016).

Moreover, PLS-SEM path modelling revealed that user friendliness positively affected the affordability of technology (hypothesis 9). This hypothesis emphasises the effects of user friendliness and its ease of use on companies' willingness to invest in new sensing technology.

Integration

The possibility of integrating different types of sensing technologies was noted in the qualitative analysis as a potential betterment and was inserted into the governance framework as a consideration. If various types of sensing technologies are compatible their integration into one system provides more accurate and robust information (Moselhi, Bardareh and Zhu 2020), which can be an outstanding motivation for adopting an integrated system of sensors. As more sensing technologies are developed and introduced to the market, a high level of integration is desirable at both the hardware and software levels of sensing technologies. This finding from the present study supports previously reported needs of promoting the integration of technologies (Nnaji et al. 2019; Moselhi, Bardareh and Zhu 2020; Elshafey et al. 2020) and the holistic integration of models and data (Dithebe et al. 2019).

7.3.2 Motivations uniquely related to the adoption of sensors

Aside from the common benefits and motivations, some motivations were identified in the governance framework that are uniquely related to the adoption of sensing technologies in particular. Unique motivations are outlined and discussed in the following.

Cost reduction

The governance framework suggests the adoption of sensing technologies can reduce the ongoing cost of a construction project through automated data collection, avoiding human error, avoiding rework and manual work reduction. Similarly, Alizadehsalehi and Yitmen (2018) reported that the use of data capturing technologies and remote visual inspections in construction progress monitoring can help to minimise rework and significantly reduce the ongoing cost of construction. Reduction of errors was also reported by Heller and Orthmann (2014) as a benefit the construction industry can get from implementing WSN during the construction phase.

Moreover, the qualitative analysis revealed that sensing technologies are effective in supply chain management by tracking and monitoring construction materials, equipment and resources to avoid losses. Avoiding material loss promotes cost reduction as well as staying on schedule. This finding supports the reported motivation of reducing faults and losses by using wireless technologies in construction (Heller and Orthmann 2014).

Effectiveness

The effectiveness of a new sensing technology is a necessity to sensing technology adoption and consists of desired attributes and requirements for the proposed sensing technologies to fit the intended purpose in construction. These requirements need to be taken into consideration during the proposal and decision making phases along with relevant benefits and barriers. The governance framework suggests that there are various attributes for a new sensing technology to be effective and suitable to improve construction performance. According to the governance framework, these attributes are durability, deployability, field practicality, reliability, repeatability, and compatibility with the rest of the system.

Lack of perceived suitability (Sardroud 2014) makes the adoption process more difficult. A suitable type of sensing technology should satisfy a wide range of requirements if it is to be effective in its purpose of improving construction performance. These requirements are covered among the factors related to the effectiveness of the sensing technology in the governance framework. Although some of these requirements were reported in the case of adopting other types of technologies, they all should be satisfied in a low-risk adoption of sensing technology. A suitable sensing technology should reliably produce valid information (Sardroud 2014; Sepasgozar et al. 2018; Dithebe et al. 2019; Nnaji et al. 2019), be repeatable (Robert-Lachaine et al. 2017; Schall et al. 2015) and be compatible with other devices in use (Sepasgozaar, Shirowzhan and Wang 2017). Another influential factor is technology durability to secure required lifespan (Dithebe et al. 2019; Nnaji et al. 2019).

Proof of effectiveness of a new technology plays an important role in motivating construction stakeholders of sensing technology implementation and facilitates its adoption and implementation processes. Proof of effectiveness could be demonstrated in different ways such as trials, obtaining feedback from previous users, or by examining the track records of successful use in similar projects in construction or other industries. Demonstrated effectiveness, as shown in the PLS-SEM path modelling, affects user friendliness of technology and technical constraints (hypotheses 5 and 6). Technology effectiveness in this research can be compared to technology usefulness in previous studies. For example, technology usefulness and demonstration projects have been reported to have a significant impact on perceived usefulness, and therefore expedite the adoption of emerging technology in the development of smart construction systems (Yang, Wang and Sun 2018). The opportunity for trial sessions was noted as a motivation to choose a new sensing technology and to test its effectiveness and suitability for specific requirements of construction projects. This accords with a previous finding that vendors can facilitate the process of decision making for technology adoption by offering trial demonstrations or access to referees (Sepasgozar and Davis 2018). Likewise, construction stakeholders who are interested in a certain technology but have no previous experience with it, usually try to inquire about it from other experts who have adopted it before (Sepasgozar et al. 2018).

Being independent

By acquiring and mastering suitable sensing technologies, construction companies will become independent from third parties performing the work. The qualitative analysis highlights the motivation of becoming independent when different management styles between stakeholders from different professions collaborating together (Redwood et al. 2017) causes complications to technology adoption and implementation. This would be the case if the construction companies needed to rely on external collaboration with IT companies. Inseparable from the independence is proper skill acquisition, either in the form of training staff or employing experts. This is why large construction companies intend for their internal skilled staff to be independent in handling breakdowns (Sepasgozar and Loosemore 2017).

7.3.3 Common barriers to new digital technology adoption

The fragmented and temporary nature of construction projects is most likely behind the majority of barriers to the implementation of emerging digital technologies (Adriaanse, Voordijk and Dewulf 2010) including new sensing technologies. In this section, common barriers and challenges mutual for the adoption of sensing technologies and during the adoption of other types of innovative technologies are outlined and discussed.

Financial constraints

Financial constraints have always been a major barrier to technology adoption in the construction industry, as outlined in the governance framework and reported in the literature (Amusan et al. 2018; Alizadehsalehi and Yitmen 2018; Dithebe et al. 2019; Olaniyan 2019; Odubiyi, Aigbavboa and Thwala 2019). Various cost-related barriers negatively impact the adoption of sensing technologies as is the case with other innovative technologies. High investment costs (Sardroud 2014; Alreshidi, Mourshed and Rezgui 2017), ongoing maintenance costs (Sardroud 2014; Dithebe et al. 2019) and uncertainties on the profits and return of investment (Sardroud 2014; Amusan et al. 2018) were identified as barriers to the adoption of different types of innovative IT-based technologies in construction. Moreover, the high cost of employing ICT professionals along with training costs (Akinbile and Oni 2016; Amusan et al. 2018) and BIM training costs (Alreshidi, Mourshed and Rezgui 2017) were also reported to negatively impact the adoption of these two technologies in construction.

Skill acquisition

Inadequate training and lack of skilled staff are well-known barriers in emerging technology adoption as revealed in the governance framework developed in this study, and in the literature (Dithebe et al. 2019; Olaniyan 2019). Most new emerging technologies require a high level of expertise (Didehvar et al. 2018; Alizadehsalehi and Yitmen 2018) and a high level of training (Nnaji et al. 2019), both of which are determinants of perceived ease of use (Son et al. 2012) among construction workers. Meanwhile, lack of professional staff leads to management problems (Sardroud 2014) during technology adoption, implementation and operation. Likewise, the level of available technical support against required technical support also significantly influence the adoption of any innovative technology in construction (Nnaji et al. 2019).

Lack of or inadequate training for construction employees (Akinbile and Oni 2016; Alreshidi, Mourshed and Rezgui 2017) and a lack of well-trained staff and professionals (Rogers, Chong and Preece 2015; Dithebe et al. 2019; Amusan et al. 2018) are examples of barriers related to skill acquisition reported in the literature with regard to the adoption of other types of digital technologies in construction.

Cultural and organisational barriers

As illustrated in the governance framework, business principles work beyond every other internal or external barrier or motivation and governs the decision making on new sensing technology adoption. When business principles facilitate innovation, a more facile sensing technology adoption is expected while a “no innovative culture” in an organisation is a major barrier to emerging technology adoption (Sardroud 2014). This aligns with the fact that company culture (Olaniyan 2019; Nnaji et al. 2019) and organisational barriers (Golizadeh et al. 2019; Borhani 2016) considerably influence the adoption and implementation of emerging technologies in construction.

The governance framework confirms that the attitudes of staff and management (Odubiyi, Aigbavboa and Thwala 2019) towards a new technology, either in the form of key stakeholders’ support or employees’ acceptance, is a prominent factor in sensing technology adoption. Moreover, construction companies usually show resistance to wide implementation of new technologies mainly because they familiar with and comfortable utilising traditional and conventional methods (Sardroud 2014; Dithebe et al. 2019).

Such barriers were also previously reported in the case of the adoption of similar technologies in construction. Lack of interest in ICT devices (Usman and Said 2012), absence of commitment to change (Olaniyan 2019) and resistance to the adoption of BIM (Alreshidi, Mourshed and Rezgui 2017) in construction represent levels of resistance to change in the construction industry. However, a contrary point of view was detected in the literature, in that resistance to change can pose problems but does not always influence innovation adoption (Sargent, Hyland and Sawang 2012). As to handling this challenge, interaction and consultation with individuals in different positions and levels is reported to be effective in the decision process (Sepasgozar and Davis 2018).

Lack of technology awareness

Reported barriers that can be rectified by raising awareness include a lack of sufficient information about the benefits and effectiveness of technology adoption on project performance (Alizadehsalehi and Yitmen 2018) and a lack of understanding about the implementation process and suitability of automated data collection technologies (Sardroud 2014). Technology awareness on the other hand, positively affects organisational support and willingness to technology adoption (Hong et al. 2016).

The governance framework shows that the education and awareness of people involved in adopting and using sensing technologies affects the process of sensing technology adoption. The interviewees acknowledged they would like to see an increase in awareness of benefits, applications and suitability of sensing technologies in the context of construction management for a more efficient technology adoption and implementation process. Increased awareness about sensing technologies facilitates technology acceptance through increasing perceived usefulness and perceived ease of use (Lee, Yu and Jeong 2015). Similar suggestions were observed in the results of previous studies indicating that increasing the awareness of innovations will contribute to their adoption such as ICT (Usman and Said 2012), BIM (Hong et al. 2016; Alreshidi, Mourshed and Rezgui 2017) and 3D scanning technology (Sepasgozaar, Shirowzhan and Wang 2017).

7.3.4 Barriers uniquely related to the adoption of sensors

Aside from the common barriers between the adoption of sensing technologies and other digital technologies, some barriers were identified in the governance framework that are uniquely related to the adoption of sensing technologies. Unique barriers are outlined and discussed in the following. These barriers have either been previously reported in the literature (only in case of a sensing technology), or are solely the outcomes of this research.

Technical barriers

Several barriers uniquely related to sensing technology adoption that were identified in this research concern technical issues ranging from technology immaturity (Sardroud 2014) to complications during implementation (Alizadehsalehi and Yitmen 2018) or operational difficulties (Usman and Said 2012; Golizadeh et al. 2019) such as difficulties during calibration, massive data capturing, processing and control (Alreshidi, Mourshed and Rezgui 2017) and maintenance. Technology immaturity covers a wide range of issues such as a lack of construction-specific ICT devices (Usman and Said 2012), range issues, inadequate power supply (Akinbile and Oni 2016), lack of software or hardware compatibility (Sardroud 2014; Didehvar et al. 2018) and inadequate durability of wearable sensors (Schall, Sesek and Cavuoto 2018).

Moreover, according to the results from PLS-SEM path modelling, technical barriers affect user friendliness of the technology (Hypothesis 8). This indicates that the more technical barriers are associated with a new sensing technology, the more important user friendliness of the technology and its ease of use would be.

Safety concerns

The governance framework indicates there are some barriers to the adoption of sensing technologies which are related to field issues ranging from safety concerns to interference with essential activities.

Safety concerns are high priority barriers to the adoption and implementation of sensing technologies in some cases. Obviously, no safety risks should be taken when implementing new technology in construction. In particular, the type of proposed sensing technology for sensitive construction sites (such as areas in the vicinity of hydrocarbon processing facilities in oil and gas industry), must be intrinsically safe. This finding supports the contribution of previous studies on developing and proposing intrinsically safe sensors for explosive environments (Zhang et al. 2016).

Ethical concerns

When the use of sensing technologies involves collecting data from people or collaboration with third parties, there will always be some ethical concerns that might affect the adoption process. For example, ownership of data or the model (if applicable) involves some ethical concerns such as in the case of BIM governance (Alreshidi, Mourshed and Rezgui 2017). Moreover, the governance framework detected concerns about security features of the new system and collected data, which supports previous findings in the literature (Usman and Said 2012; Häikiö et al. 2020). For example, public backlash and complaints regarding the use of drones on construction sites next to residential areas were identified in the qualitative analysis. This supports the previous finding that restrictive regulations pose major barriers to the use of drones in construction projects (Golizadeh et al. 2019).

Ethical issues initiate even more complications for the adoption process of a sensing technology especially if personal information of staff might be disclosed to a second party. Schall, Sesek, and Cavuoto (2018) reported concerns about employees' privacy, confidentiality and compliance regarding the use of wearable sensors. In support of this, some interviewees in the present study acknowledged the main barrier behind not using wearable sensors is an ethical concern regarding the privacy of collected data and rigid constraints imposed by trade unions or workers' representatives.

Former unsuccessful experience

One unique barrier to sensing technology adoption identified in this research was having some form of previous unsuccessful experience with the same or a similar sensing technology being considered during the proposal phase of technology adoption. Interviewees in the present study said former unsuccessful experiences influence decision makers and causes some resistance to their openness to try a new sensing technology. Any hesitation as a result of a previous unsuccessful experience should be addressed through a demonstration of the effectiveness, which is proposed in the motivating framework (see Figure 6.5). Demonstrated effectiveness of a new sensing technology might occur through either industry trials with adequate support from vendors, or successful industry showcases.

7.4 Summary

In the first half of this chapter, findings from the four objectives were outlined and explained. Since objectives 1 and 2 focused on the current status of sensing technologies in the literature and in actual construction projects, the most frequently researched sensing technologies for improving construction performance were identified in a review of literature. The results of the review were investigated by an online survey aimed at discovering the current status of the utilisation of those technologies in real construction projects. A comparison of findings related to these two objectives, clearly indicates that the construction industry still has a long way ahead in the uptake of sensing technologies that are developed and proven through research to be applicable and effective in improving construction safety, productivity or quality. Objective 3 was dedicated to discovering the factors that promote or hinder the adoption of sensing technologies in construction. Findings related to objective 3 were extracted from the literature review, the online survey or the interviews. Those findings then informed the governance framework, which was the aim of objective 4. Two secondary frameworks based on the governance framework, specify and explain in more detail how the framework applies to motivation and appraisal processes.

In the second half of this chapter, the contribution of the governance framework was discussed. The governance framework was compared to similar works identified in the literature, and different factors and categories of factors that comprised the governance framework were compared to previous research in similar areas. Motivations and barriers common to the adoption of sensing technologies and the adoption of other types of digital technologies were discussed. Common motivations were “improved performance”, “vendor/supplier support”, “user friendliness” and “integration”, whereas common barriers were “financial constraints”, “skill acquisition”, “cultural and organisational barriers” and “lack of technology awareness”. Motivations and barriers unique to the adoption of sensing technologies were also outlined. Unique motivations were recognised as “cost reduction”, “effectiveness” and “being independent”, while unique barriers were identified as “technical barriers”, “safety concerns” and “ethical concerns”.

Chapter Eight

8

Conclusion, Contribution and Future Recommendations

8.1 Introduction

In this final chapter, the research conclusion and contributions to the body of knowledge are explained. Furthermore, practical implications of the research are outlined and limitations associated with the conduct of this research and recommendations for future studies are specified.

8.2 Conclusion

This research was a step forward towards understanding the application and suitability of sensing technologies to improve construction performance, and to discover the rationale behind the slow adoption of such technologies on construction sites and in construction management practices. The findings outlined the sensing technologies most noted in the literature that were applicable to various areas of construction management with the aim of improving construction performance. In this study, the focus was on those sensing technologies that have been reported to be effective in improving construction safety, productivity or quality. The study confirms findings in the literature that the adoption of sensing technologies in construction projects is slow, despite their huge potential to improve construction performance. Eight different types of sensing technologies (GPS, RFID, UWB, FOS, pressure sensing, temperature sensing, visual sensing and 3D scanning) were selected and an analysis made of the extent to which these technologies were being used in building, infrastructure and industrial sectors of the construction industry. It was found that the implementation status of the selected sensing technologies is way behind their capabilities to improve construction performance. A cross-sector comparison on the current status of sensing technology implementation revealed industrial construction led the uptake of sensing technologies, whereas building construction was far behind. An analysis also showed that even popular technologies such as GPS and visual sensing are not adopted by many building and infrastructure construction companies. The adoption rate of other sensing technologies such as RFID and FOS was even lower than GPS and visual sensing.

In order to counter current practices in the construction industry and promote innovative sensing technologies, there is a need to raise awareness of the advantages of these technologies and added value that results from their implementation. As an initial step towards achieving this purpose, a governance framework was developed, which was the ultimate aim of this research. The governance framework accommodates factors affecting the adoption and acceptance of sensing technologies in construction. The framework consists of a core structure that depicts the process of sensing technology adoption, beginning with proposal for new sensing technology that can improve construction performance, followed by evaluation and approval of the proposed sensing technology. Only when the proposed sensing technology is approved, the implementation phase occurs. Various factors are associated with each phase of sensing technology adoption in the governance framework. Barriers and motivations work in opposite directions during the proposal, while there are considerations to be taken into account to minimise any risk associate with introducing new devices into the existing systems. When the totality of motivations, barriers and all relevant considerations conclude a new sensing technology is suitable for an intended role in a construction project, the proposal progresses to detailed evaluation and approval. During the evaluation, considerations for the suitability of the proposed sensing technology, whole of life costs, and factors related to people should be justified.

The governance framework can be referred to for easier decision making on the suitability of a particular sensing technology to fit a specific purpose in construction. It is concluded that among common barriers, the capital cost of sensing technology implementation is the strongest barrier to its adoption. As a result of this study, it can be concluded that the slow adoption of sensing technologies in construction is not only because of barriers common to most emerging technologies, but also barriers that are unique to the adoption of sensors. These unique barriers are technical barriers, safety concerns, and ethical concerns. Aside from financial constraints and challenges related to skill acquisition, another common barrier to technology adoption, but outstanding in the case of sensing technology, was related to decision makers or end users who were described as being resistant to change and who lacked awareness of the benefits of a proposed new technology. Such barriers could be diminished by raising awareness of the benefits and effectiveness of the intended sensing technology.

8.3 Contributions

This research investigated challenges that affected the adoption of innovative sensing technologies to improve construction performance. The main contributions of this research when compared to similar studies with results published in the literature, are summarised as the following:

1. **Focusing on the adoption of sensing technologies rather than general technology adoption or even the adoption of ICT in construction.**

   The first contribution of this research relates to its comprehensive inclusion of various types of sensing technologies and different scopes of construction management that would be affected by using sensing technologies.

   Most review articles on the applicability of sensing technologies in construction were either dedicated to one group of technologies (for example, the application of FOS (Afzal, Kabir and Sidek 2012; Ye, Su and Han 2014), RTLS (Soltanmohammadlou et al. 2019; Moselhi, Bardareh and Zhu 2020), wearable sensors (Kamišalić et al. 2018; Awolusi, Marks and Hallowell 2018; Mukhopadhyay 2015; Ahn et al. 2019), etc.) or defined within a specific scope of construction management (for instance, supply chain management (Shi et al. 2016), construction safety monitoring (Awolusi, Marks and Hallowell 2018) or OHS (Antwi-Afari et al. 2019; Ahn et al. 2019), etc.). In contrast, this present research reviewed the application of various types of sensing technologies (ranging from location-based sensing to vision-based, WSN and wearable sensors) applicable to different areas of construction management (safety including OHS, productivity and quality).

2. **Current implementation status of eight different types of sensing technologies through direct inquiring from construction professionals across three sectors of the construction industry.**

   The majority of previous studies on sensing technologies focused on experiment-based results (Aryal, Ghahramani and Becerik-Gerber 2017; Cheng and Teizer 2013) or case studies (Fang et al. 2016; Siddiqui, Vahdatikhaki and Hammad 2019; Ozumba et al. 2019) regarding the applicability and suitability of sensors in construction management. This research took a step forward by investigating the extent to which selected technologies have already been implemented across different sectors of the construction industry. Quantitative analysis of the current status of eight different types of sensing technologies in three sectors of construction industry (building, infrastructure and industrial construction), revealed that despite huge potentials reported in the literature, several types of sensing technologies are not still adopted by the majority of construction companies. Therefore, this research confirmed the slow adoption of sensing technologies in construction based on the current implementation status of eight different types of sensing technologies most commonly identified in the literature.

3. **Identification of factors that are uniquely related to sensing technology adoption in addition to reviewing and confirming the importance of common factors that affect the adoption of various types of innovative technologies in construction.**

The third contribution of this research was related to the factors that affect the adoption of sensing technologies in the construction industry. These factors were either discovered in this research for the first time (unique motivations and unique barriers discussed in 7.3.2 and 7.3.4, respectively) or identified in the literature regarding the adoption of other technologies and confirmed in this study for sensing technology adoption (common motivations and common barriers discussed in 7.3.1 and 7.3.3, respectively). The process of achieving this contribution began with reviewing the construction stakeholders' perceptions of sensing technologies and to identify factors they believe affect the adoption of such technologies in construction. This literature review, as opposed to previous reviews, was not limited to a specific group of technologies, such as the adoption of wearable sensors (Schall, Sesek and Cavuoto 2018), ICT (Usman and Said 2012) and ADC (Sardroud 2014). Rather, this present review embraced all relevant factors reported in the literature regarding the adoption of almost all types of innovative digital technologies in construction. Additionally, this review was not only limited to the factors affecting the adoption but also covered factors affecting the acceptance of sensing technologies by construction workers. This literature review was even inclusive of factors that affect the adoption of other categories of innovative digital technologies and so its comprehensive had a pivotal role in the design of the quantitative and qualitative methods used for data collection during this research.

The common factors reported in the literature were about the adoption of other types of technologies, not only sensing technologies, but were examined for their significance in the case of sensing technology adoption through PLS-SEM path modelling. The PLS-SEM model indicated that the factors identified in the literature also significantly affected the adoption and acceptance of sensing technologies in construction. The path modelling also revealed which of the factor groupings significantly affected others. The results of the PLS-SEM path modelling contribute to the body of knowledge regarding the factors that significantly affect the adoption of all types of sensing technologies in particular, as opposed to previous studies that considered the adoption and acceptance of a specific type of sensing technology

(Sepasgozaar, Shirowzhan and Wang 2017; Schall, Sesek and Cavuoto 2018; Jacobs et al. 2019) or those that studied the construction technology adoption in general (Sepasgozar and Bernold 2013b; Nnaji et al. 2019).

The factors that are uniquely related to sensing technology adoption were identified by qualitative data collection and analysis through interviews with key construction stakeholders and decision makers. The interviews identified major considerations that play critical roles in the decision making of sensing technology adoption, confirming common factors and then declaring the existence of some unique factors. These unique factors were not detected in the literature, and therefore are recognised as the main part of the third contribution. Embracing a wide range of factors, this research identifies as a rich source of information regarding influential factors on sensing technology adoption and implementation in the construction industry.

4. **Development of three frameworks to assist with the adoption of sensing technologies in construction: a governance framework, a motivating framework and an appraisal framework.**

The ultimate contribution of this research is the development of the governance framework, embracing a wide range of influential factors relating to the adoption of sensing technologies in construction. The governance framework presents detailed factors that affect the adoption and implementation of sensing technologies throughout the adoption process of such technologies in construction. The governance framework contributes to the body of knowledge with regard to the incorporation of different factors that might promote or inhibit the adoption and implementation of any kind of sensing technology in construction, either uniquely related to sensing technology adoption or common between sensing technology adoption and the adoption of some other types of technologies.

The governance framework also contributed to the development of two more specific frameworks: a motivating framework and an appraisal framework. The motivating framework focuses specifically on the motivations derived from the governance framework and represents how construction decision makers usually become motivated to adopt a new sensing technology and highlights how certain barriers can be transformed into motivations through suitable solutions. The appraisal framework focuses on assessment considerations for decision making on a low-risk adoption of a new sensing technology in construction. This framework consists of critical questions regarding the appropriateness of a proposed sensing technology and explicitly features decision making considerations to minimise complications and challenges of sensing technology implementation during construction. The most noticeable contribution of these two supplementary frameworks is related to their practical implications for decision making on sensing technology.

8.4 Practical Implications

This research will help key stakeholders and decision makers in the construction industry to more clearly and deeply perceive the suitability of different types of sensing technologies and associated applications in construction management practices. The following practical implications are envisaged from the outcome of this research.

- The PLS-SEM path model is useful for optimising different sets of factors that influence the adoption and implementation of sensing technologies in construction. The results from this model acknowledge which factors are more important than others regarding the adoption of new sensing technologies and how some factors might affect other factors. By using the results of this PLS-SEM model, construction stakeholders and decision makers can work around factors that are more critical to their specific project against those factors that might be of less importance, knowing how the critical factors in their business are affected by the alteration of other sets of factors within the PLS-SEM model.
- The governance framework is a detailed resource of factors affecting the adoption of sensing technologies in construction. This framework has the ability to act as a reference for construction stakeholders in the decision making process of sensing technology adoption. The governance framework is quite comprehensive, hence not all factors will apply to every single case of sensing technology adoption process. Even in the case of a single sensing technology, the characteristics of a construction site and project might demand a different set of factors. For example, construction sites in harsh environments might require more durable devices, or explosion-sensitive construction sites might require intrinsically safe sensors. The same concept is valid for different types of sensing technologies for the same construction site. Meaning, some factors inside the governance framework might apply to one type of sensing technology and might not apply to another type of technology for the same construction site. Yet, the comprehensiveness of the governance framework makes it applicable to all types of sensing technologies in any construction environment. Referring to the governance framework, construction decision makers can minimise the risks associated with the adoption of a new sensing technology since detailed factors and considerations are foreseen in this framework.

- The motivating framework can be applied during the proposal of a new sensing technology. The framework helps with demonstrating benefits and motivations that support a wider use of sensing technologies in construction. As for a new sensing technology being proposed, the motivating framework can demonstrate interconnected motivations and benefits envisaged with implementation. It can also help construction stakeholders with transforming specific barriers into motivations. For example, a suitable action such as testing the new sensing technology in trial sessions might transform a barrier of "former unsuccessful experience" into a motivation of "demonstrated effectiveness" that is achievable through support from vendors.
- The appraisal framework can be applied during the evaluation and before the approval of a proposed sensing technology. The framework questions the suitability of a nominated sensing technology for an intended purpose in construction and tries to minimise the possibility of future risks associated with introducing new components (sensors) into the old system. The appraisal framework is easy to follow and contains key considerations essential for the assessment of a proposed sensing technology.

8.5 Limitations

The first limitation of this research was to exclude sensors for testing purposes as it did not fit the scope. As explained in Chapter 2, the scope of the literature review was to consider sensors suitable for continuous monitoring in order to improve construction safety, quality or productivity. Considering the fact that testing procedures are usually prerequisites to a construction phase or even the design stage, sensors used for testing purposes fall outside of the scope of this study. In addition, the adoption of sensing technologies in general was the focus of this research rather than specific types of sensors. Although this approach enabled a wide range of factors to be covered and for a comprehensive governance framework to be developed and applicable to a wide range of sensing technologies, the study may lack some technology-specific attributes.

This research does not include the current status of the use of wearable sensing technologies in the Australian construction industry. That is mostly due to the fact that such types of devices are still in the preliminary stages of research and not yet exploited on real construction sites, as indicated in interview discussions and the literature (Borhani 2016). However, wearable sensors were considered to be a range of sensing technologies with great potential to improve construction performance. The study identified major factors affecting the adoption of these technologies in construction.

Another limitation was associated with sample sizes for the quantitative and qualitative methods and their limitation to Australian construction companies. Although the number of survey responses and interviews were enough to satisfy the requirement for research and provided data saturation, a larger sample size would provide more accurate results, especially with regard to the current status of sensing technologies and path modelling of influential factors.

8.6 Recommendations

The following recommendations are nominated for future research, taking into account the findings from this research and also the limitations associated with it.

1. **Research on the ethical requirements for a more facile sensing technology adoption**

   One of the research findings was that the adoption of sensing technologies which involve data collection from individuals raises ethical concerns. It is recommended to research how ethical concerns behind the implementation of sensing technologies can be addressed. A study should cover the points of views of stakeholders inside and outside of the construction industry. For example, trade unions react strongly to personal data collection from employees. This should be included and addressed in future research in this area.

2. **Case study on a specific sensing technology adoption using the governance framework**

   It is recommended that the governance framework presented in this research be used in a case study for the adoption of any type of sensing technology in construction. The case study could be conducted in any sector of the construction industry and since the governance framework covers a wide range of factors, it can be applied to almost any type of sensing technology. One possible result of the case study could be a modified and customised framework extracted from the governance framework to accommodate specific requirements associated with the particular sensor under study. Such research can cover any latent technology-specific factor which might affect the adoption process of that technology and is not covered in the governance framework. It is recommended that one specific type of sensing technology not widely adopted during construction be nominated and the reasons behind its slow adoption be explored. One potential example is a company's view of the adoption of wearable sensors since previous studies mostly focused on the employees' acceptance of wearables rather than factors affecting the adoption process at a company level.

3. **Research on the adoption of sensing technologies from an international point of view**

As mentioned in the limitations, the data collection for this thesis was limited to Australian construction companies and their use of sensing technologies to improve construction safety, productivity or quality. Likewise, only Australian construction professionals participated in this research, with their perceptions of sensing technologies and which factors they believe affect the adoption of such technologies in construction. It is recommended that a similar study be conducted with international or multi-cultural data collection, to determine which countries lead the way towards sensing technology implementation during construction. Such research can analyse and conclude how those counties have dealt with and overcome the barriers. This might identify more motivations and solutions that rectify barriers in the construction industries of countries still resistant to the adoption of sensing technologies.

4. **Knowledge transfer from pioneer industries in the uptake of sensing technologies to construction industry**

As noted repeatedly in the literature and confirmed in this research, the construction industry lags behind other industries in the uptake of sensing technologies. To address this lag, this research has studied the factors affecting sensing technology adoption in the construction industry. It is recommended that future research use the findings from this research to address the issue from a different point of view: how have other industries managed to adopt and implement more sensing technologies? Future research can focus on a pioneer industry in the uptake of sensing technologies (for example mining operations, manufacturing, etc.) to develop a plan to transfer knowledge that leads to a wider adoption and implementation of sensing technologies in the construction industry.

References

Adjiski, Vancho, Zoran Despodov, Dejan Mirakovski, and Dalibor Movski. 2019. "System Architecture to Bring Smart Personal Protective Equipment Wearables and Sensors to Transform Safety at Work in the Underground Mining Industry." *Rudarsko - Geolosko - Naftni Zbornik* 34 (1): 37-44. https://doi.org/10.17794/rgn.2019.1.4.

Adriaanse, Arjen, Hans Voordijk, and Geert Dewulf. 2010. "Adoption and Use of Interorganizational Ict in a Construction Project." *Journal of construction engineering and management* 136 (9): 1003-1014. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000201.

Afzal, Muhammad Hassan Bin, Shahid Kabir, and Othman Sidek. 2012. "An in-Depth Review: Structural Health Monitoring Using Fiber Optic Sensor." *IETE Technical Review* 29 (2): 105-113. https://doi.org/10.4103/0256-4602.95383.

Aghimien, Douglas, Clinton Aigbavboa, Ayodeji Oke, and Nteboheng Koloko. 2018. 'Digitalisation in Construction Industry: Construction Professionals Perspective.' December.

Ahmad, Zubair, Muhammad Jamaluddin Thaheem, and Ahsen Maqsoom. 2018. "Building Information Modeling as a Risk Transformer: An Evolutionary Insight into the Project Uncertainty." *Automation in Construction* 92: 103-119. https://doi.org/https://doi.org/10.1016/j.autcon.2018.03.032.

Ahmed, Vian, Zeeshan Aziz, Algan Tezel, and Zainab Riaz. 2018. "Challenges and Drivers for Data Mining in the Aec Sector." *Engineering, Construction and Architectural Management* 25 (11): 1436-1453. https://doi.org/10.1108/ECAM-01-2018-0035.

Ahn, Changbum R., SangHyun Lee, Cenfei Sun, Houtan Jebelli, Kanghyeok Yang, and Byungjoo Choi. 2019. "Wearable Sensing Technology Applications in Construction Safety and Health." *Journal of Construction Engineering and Management* 145 (11): 03119007. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001708.

Akhavian, Reza, and Amir H. Behzadan. 2015. "Construction Equipment Activity Recognition for Simulation Input Modeling Using Mobile Sensors and Machine Learning Classifiers." *Advanced Engineering Informatics* 29 (4): 867-877. https://doi.org/10.1016/j.aei.2015.03.001.

Akinbile, B. F., and O. Z. Oni. 2016. "Assessment of the Challenges and Benefits of Information Communication Technology (Ict) on Construction Industry in Oyo State Njgeria." *Annals of the Faculty of Engineering Hunedoara* 14 (4): 161-166.

Akinci, Burcu, Frank Boukamp, Chris Gordon, Daniel Huber, Catherine Lyons, and Kuhn Park. 2006. "A Formalism for Utilization of Sensor Systems and Integrated Project Models for Active Construction Quality Control." *Automation in Construction* 15 (2): 124-138. https://doi.org/10.1016/j.autcon.2005.01.008.

Alarifi, Abdulrahman, AbdulMalik Al-Salman, Mansour Alsaleh, Ahmad Alnafessah, Suheer Al-Hadhrami, Mai Al-Ammar, and Hend Al-Khalifa. 2016. "Ultra Wideband Indoor Positioning Technologies: Analysis and Recent Advances." *Sensors (Basel)* 16 (5): 707. https://doi.org/10.3390/s16050707.

Alfar, Mohamad. 2016. 'Integration of Innovation in Construction Management.' edited by Murat Gunduz, Ramzy Taha, Dinesh Seth and Okan Sirin: ProQuest Dissertations Publishing.

Alizadehsalehi, Sepehr, and Ibrahim Yitmen. 2018. "A Concept for Automated Construction Progress Monitoring: Technologies Adoption for Benchmarking Project Performance Control." *Arabian journal for science and engineering (2011)* 44 (5): 4993-5008. https://doi.org/10.1007/s13369-018-3669-1.

Alreshidi, Eissa, Monjur Mourshed, and Yacine Rezgui. 2017. "Factors for Effective Bim Governance." *Journal of Building Engineering* 10 (C): 89-101. https://doi.org/10.1016/j.jobe.2017.02.006.

Alyahmady, Hamed Hilal, and Saleh Said Al Abri. 2013. "Using Nvivo for Data Analysis in Qualitative Research." *International Interdisciplinary Journal of Education* 2 (2): 181-186. https://doi.org/10.12816/0002914.

Amusan, LM, Leke I Oloniju, Mariam Akomolafe, Adebisi Makinde, Nkolika Joy Peter, Hezekiah Farayola, and FAITH Osawaru. 2018. "Adopting Information and Communication Technology in Construction Industry." *International Journal of Mechanical Engineering and Technology (IJMET)* 9 (1): 739-746.

Antwi-Afari, M. F., H. Li, D. J. Edwards, E. A. Pärn, J. Seo, and A. Y. L. Wong. 2017. "Biomechanical Analysis of Risk Factors for Work-Related Musculoskeletal Disorders During Repetitive Lifting Task in Construction Workers." *Automation in Construction* 83: 41-47. https://doi.org/https://doi.org/10.1016/j.autcon.2017.07.007.

Antwi-Afari, Maxwell Fordjour, Heng Li, Johnny Kwok-Wai Wong, Olugbenga Timo Oladinrin, Janet Xin Ge, Joonoh Seo, and Arnold Yu Lok Wong. 2019. "Sensing and Warning-Based Technology Applications to Improve Occupational Health and Safety in the Construction Industry: A Literature Review." *Engineering, Construction and Architectural Management*: 05-2018-0188. https://doi.org/10.1108/ECAM-05-2018-0188.

Aryal, Ashrant, Ali Ghahramani, and Burcin Becerik-Gerber. 2017. "Monitoring Fatigue in Construction Workers Using Physiological Measurements." *Automation in Construction* 82: 154-165. https://doi.org/https://doi.org/10.1016/j.autcon.2017.03.003.

Awolusi, Ibukun, Eric Marks, and Matthew Hallowell. 2018. "Wearable Technology for Personalized Construction Safety Monitoring and Trending: Review of Applicable Devices." *Automation in Construction* 85: 96-106. https://doi.org/10.1016/j.autcon.2017.10.010.

Barro-Torres, Santiago, Tiago M. Fernández-Caramés, Héctor J. Pérez-Iglesias, and Carlos J. Escudero. 2012. "Real-Time Personal Protective Equipment Monitoring System." *Computer Communications* 36 (1): 42-50. https://doi.org/10.1016/j.comcom.2012.01.005.

Behzadan, Amir H., Zeeshan Aziz, Chimay J. Anumba, and Vineet R. Kamat. 2008. "Ubiquitous Location Tracking for Context-Specific Information Delivery on Construction Sites." *Automation in Construction* 17 (6): 737-748. https://doi.org/10.1016/j.autcon.2008.02.002.

Bentler, Peter M., and Wenjing Huang. 2014. "On Components, Latent Variables, Pls and Simple Methods: Reactions to Rigdon's Rethinking of Pls." *Long Range Planning* 47 (3): 138-145. https://doi.org/10.1016/j.lrp.2014.02.005.

Biedenbach, Thomas, and Mattias Jacobsson. 2016. "The Open Secret of Values: The Roles of Values and Axiology in Project Research." *Project Management Journal* 47 (3): 139-155. https://doi.org/10.1177/875697281604700312.

Bonchis, Adrian, Elliot Duff, Jonathan Roberts, and Mike Bosse. 2014. "Robotic Explosive Charging in Mining and Construction Applications." *IEEE Transactions on Automation Science and Engineering* 11 (1): 245-250. https://doi.org/10.1109/TASE.2013.2241425.

Borhani, Atieh Sadat. 2016. 'Individual and Organizational Factors Influencing Technology Adoption for Construction Safety.' ProQuest Dissertations Publishing.

Brilakis, Ioannis, Sanghyun Lee, and Burcin Becerik-Gerber. 2013. 'Application of Sensing Technology in the Prevention of Backing Accidents in Construction Work Zones.' In *ASCE International Workshop on Computing in Civil Engineering*, Reston, VA: Reston, VA: American Society of Civil Engineers.

Byrne, Barbara M. 2013. *Structural Equation Modeling with Mplus: Basic Concepts, Applications, and Programming*: routledge.

Cao, Jiannong author. 2016. *Wireless Sensor Networks for Structural Health Monitoring / Jiannong Cao, Xuefeng Liu*. Edited by Xuefeng author Liu. 1st ed. 2016.. ed: [Cham, Switzerland] : Springer.

Cassell, Catherine. 2004. *Essential Guide to Qualitative Methods in Organizational Research*. Edited by Gillian Symon. London: London : SAGE Publications.

Chae, Soungho, and Tomohiro Yoshida. 2010. "Application of Rfid Technology to Prevention of Collision Accident with Heavy Equipment." *Automation in Construction* 19 (3): 368-374. https://doi.org/10.1016/j.autcon.2009.12.008.

Charmaz, Kathy. 2006. *Constructing Grounded Theory: A Practical Guide through Qualitative Analysis*: sage.

Chen, Jiayu, Jun Qiu, and Changbum Ahn. 2017. "Construction Worker's Awkward Posture Recognition through Supervised Motion Tensor Decomposition." *Automation in Construction* 77: 67-81. https://doi.org/https://doi.org/10.1016/j.autcon.2017.01.020.

Cheng, T., M. Venugopal, J. Teizer, and P. A. Vela. 2011. "Performance Evaluation of Ultra Wideband Technology for Construction Resource Location Tracking in Harsh Environments." *Automation in Construction* 20 (8): 1173-1184. https://doi.org/https://doi.org/10.1016/j.autcon.2011.05.001.

Cheng, Tao, and Jochen Teizer. 2013. "Real-Time Resource Location Data Collection and Visualization Technology for Construction Safety and Activity Monitoring Applications." *Automation in Construction* 34: 3-15. https://doi.org/10.1016/j.autcon.2012.10.017.

Cheng, Tao, and Jochen Teizer. 2014. "Modeling Tower Crane Operator Visibility to Minimize the Risk of Limited Situational Awareness." *Journal of Computing in Civil Engineering* 28 (3). https://doi.org/10.1061/(ASCE)CP.1943-5487.0000282.

Cheng, Tao, Jochen Teizer, Giovanni C. Migliaccio, and Umberto C. Gatti. 2013. "Automated Task-Level Activity Analysis through Fusion of Real Time Location Sensors and Worker's Thoracic Posture Data." *Automation in Construction* 29 (C): 24-39. https://doi.org/10.1016/j.autcon.2012.08.003.

Chi, Hongpeng, Kai Zhan, and Boqiang Shi. 2012. "Automatic Guidance of Underground Mining Vehicles Using Laser Sensors." *Tunnelling and Underground Space Technology* 27 (1): 142-148. https://doi.org/https://doi.org/10.1016/j.tust.2011.08.007.

Chi, Hung-Lin, J. Wang, Xiangyu Wang, M. Truijens, and P. Yung. 2015. "A Conceptual Framework of Quality-Assured Fabrication, Delivery and Installation Processes for Liquefied Natural Gas (Lng) Plant Construction."

Choi, Byungjoo, Sungjoo Hwang, and Sanghyun Lee. 2017. "What Drives Construction Workers' Acceptance of Wearable Technologies in the Workplace?: Indoor Localization and Wearable Health Devices for Occupational Safety and Health." *Automation in Construction* 84: 31-41. https://doi.org/10.1016/j.autcon.2017.08.005.

Creswell, John W. 2013. *Qualitative Inquiry & Research Design : Choosing among Five Approaches / John W. Creswell*. Edited by John W. Creswell. 3rd ed.. ed, *Qualitative Inquiry and Research Design*. Thousand Oaks: Thousand Oaks : SAGE Publications.

Creswell, John W. 2018a. *Research Design: Qualitative, Quantitative, and Mixed Methods Approaches*. 5th ed. Thousand Oaks, California: SAGE Publications, Inc.

Creswell, John W. author. 2018b. *Qualitative Inquiry & Research Design : Choosing among Five Approaches / John W. Creswell, Cheryl N. Poth*. Edited by Cheryl N. author Poth. Fourth edition.. ed, *Qualitative Inquiry and Research Design*: Thousand Oaks, California : SAGE.

Daniel, Ben Kei author. 2018. *Higher Education Research Methodology: A Step-by-Step Guide to the Research Process* Edited by Tony author Harland. 1st edition.. ed: Abingdon, Oxon : Routledge.

Darlaston-Jones, Dawn. 2007. "Making Connections: The Relationship between Epistemology and Research Methods." *Australian Community Psychologist* 19 (1).

Davis, Fred D. 1985. "A Technology Acceptance Model for Empirically Testing New End-User Information Systems: Theory and Results." Massachusetts Institute of Technology.

Davis, Fred D. 1989. "Perceived Usefulness, Perceived Ease of Use, and User Acceptance of Information Technology." *MIS quarterly* 13 (3): 319-340. https://doi.org/10.2307/249008.

Didehvar, Nasim, Mohammadnabi Teymourifard, Mohammad Mojtahedi, and Samad Sepasgozar. 2018. "An Investigation on Virtual Information Modeling Acceptance Based on Project Management Knowledge Areas." *Buildings* 8 (6): 80. https://doi.org/10.3390/buildings8060080.

Dijkstra, T. K. 2014. "Pls'janus Face: Response to Professor Rigdon's 'Rethinking Partial Least Squares Modeling: In Praise of Simple Methods'." *Long Range Planning* 47 (3): 146-153. https://doi.org/10.1016/j.lrp.2014.02.004.

Dijkstra, Theo K., and Jörg Henseler. 2015. "Consistent and Asymptotically Normal Pls Estimators for Linear Structural Equations." *Computational Statistics & Data Analysis* 81 (1): 10-23.

Ding, L. Y., C. Zhou, Q. X. Deng, H. B. Luo, X. W. Ye, Y. Q. Ni, and P. Guo. 2013. "Real-Time Safety Early Warning System for Cross Passage Construction in Yangtze Riverbed Metro Tunnel Based on the Internet of Things." *Automation in Construction* 36: 25-37. https://doi.org/https://doi.org/10.1016/j.autcon.2013.08.017.

Ding, Zhikun, Menglian Zhu, Vivian W. Y. Tam, Guizhen Yi, and Cuong N. N. Tran. 2018. "A System Dynamics-Based Environmental Benefit Assessment Model of Construction Waste Reduction Management at the Design and Construction Stages." *Journal of Cleaner Production* 176: 676-692. https://doi.org/10.1016/j.jclepro.2017.12.101.

Dithebe, K., C. O. Aigbavboa, W. D. Thwala, and A. T. Malabela. 2019. "Descriptive Perspective on Factors Affecting the Complete Adoption of Information Technology Systems in the Construction Firms." *Journal of physics. Conference series* 1378: 22045. https://doi.org/10.1088/1742-6596/1378/2/022045.

Doloi, Hemanta. 2014. "Rationalizing the Implementation of Web-Based Project Management Systems in Construction Projects Using Pls-Sem." *Journal of Construction Engineering and Management* 140 (7): 4014026. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000859.

Dong, Shuang, Heng Li, and Qin Yin. 2018. "Building Information Modeling in Combination with Real Time Location Systems and Sensors for Safety Performance Enhancement." *Safety Science* 102: 226.

Durdyev, Serdar, and Syuhaida Ismail. 2016. "On-Site Construction Productivity in Malaysian Infrastructure Projects." *Structural Survey* 34 (4/5): 446-462. https://doi.org/10.1108/SS-12-2015-0058.

El-Diraby, T. E., and K. F. Kashif. 2005. "Distributed Ontology Architecture for Knowledge Management in Highway Construction." *Journal of Construction Engineering and Management* 131 (5): 591-603. https://doi.org/10.1061/(ASCE)0733-9364(2005)131:5(591).

Elshafey, Abdalrahman, Chai Chang Saar, Eeydzah Binti Aminudin, Masoud Gheisari, and Abdulrahman Usmani. 2020. "Technology Acceptance Model for Augmented Reality and Building Information Modeling Integration in the Construction Industry." *Journal of information technology in construction* 25: 161-172. https://doi.org/10.36680/j.itcon.2020.010.

Fang, Yihai, Yong K. Cho, Sijie Zhang, and Esau Perez. 2016. "Case Study of Bim and Cloud–Enabled Real-Time Rfid Indoor Localization for Construction Management Applications." *Journal of Construction Engineering and Management* 142 (7). https://doi.org/10.1061/(ASCE)CO.1943-7862.0001125.

Fellows, Richard. 2009. "Advanced Research Methods in the Built Environment." *Construction Management and Economics* 27 (6): 605-609. https://doi.org/10.1080/01446190902896637.

Fellows, Richard F., and Anita M. M. Liu. 2015. *Research Methods for Construction*. New York, UNITED KINGDOM: John Wiley & Sons, Incorporated. http://ebookcentral.proquest.com/lib/curtin/detail.action?docID=1895747.

Feng, Y., and Peng Wu. 2015. "Risk Compensation Behaviours in Construction Workers' Activities."

Feng, Yingbin, Peng Wu, Gui Ye, and Dong Zhao. 2017. "Risk-Compensation Behaviors on Construction Sites: Demographic and Psychological Determinants." *Journal of Management in Engineering* 33 (4): 4017008. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000520.

Frambach, Ruud T., and Niels Schillewaert. 2002. "Organizational Innovation Adoption: A Multi-Level Framework of Determinants and Opportunities for Future Research." *Journal of Business Research* 55 (2): 163-176. https://doi.org/10.1016/S0148-2963(00)00152-1.

Golizadeh, Hamed, M. Reza Hosseini, David John Edwards, Sepehr Abrishami, Nasrin Taghavi, and Saeed Banihashemi. 2019. "Barriers to Adoption of Rpas on Construction Projects: A Task–Technology Fit Perspective." *Construction innovation* 19 (2): 149-169. https://doi.org/10.1108/ci-09-2018-0074.

Goodrum, Paul M., Carl T. Haas, Carlos Caldas, Dong Zhai, Jordan Yeiser, and Daniel Homm. 2011. "Model to Predict the Impact of a Technology on Construction Productivity." *Journal of Construction Engineering and Management* 137 (9): 678-688. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000328.

Grau, David, Carlos H. Caldas, Carl T. Haas, Paul M. Goodrum, and Jie Gong. 2009. "Assessing the Impact of Materials Tracking Technologies on Construction Craft Productivity." *Automation in Construction* 18 (7): 903-911. https://doi.org/10.1016/j.autcon.2009.04.001.

Guo, Hongling, Yantao Yu, Tian Xiang, Heng Li, and Dan Zhang. 2017. "The Availability of Wearable-Device-Based Physical Data for the Measurement of Construction Workers' Psychological Status on Site: From the Perspective of Safety Management." *Automation in Construction* 82: 207.

Häikiö, Juha, Johanna Kallio, Satu-Marja Mäkelä, and Janne Keränen. 2020. "Iot-Based Safety Monitoring from the Perspective of Construction Site Workers." *International Journal of Occupational and Environmental Safety* 4 (1): 1-14. https://doi.org/10.24840/2184-0954_004.001_0001.

Hair, Joseph F. Jr author. 2017. *A Primer on Partial Least Squares Structural Equation Modeling (Pls-Sem) / Joseph F. Hair, Jr., G. Tomas M. Hult, Christian M. Ringle, Marko Sarstedt*. Second edition.. ed: Thousand Oaks, California : SAGE Publications, Inc.

Hair, Joseph F., Jeffrey J. Risher, Marko Sarstedt, and Christian M. Ringle. 2019. "When to Use and How to Report the Results of Pls-Sem." *European Business Review* 31 (1): 2-24. https://doi.org/10.1108/EBR-11-2018-0203.

Hair Jr, Joseph F, G Tomas M Hult, Christian Ringle, and Marko Sarstedt. 2016. *A Primer on Partial Least Squares Structural Equation Modeling (Pls-Sem)*: Sage publications.

Hamilton Lopes Miranda, Junior, Bezerra Nelson Roberto Albuquerque, Bezerra Marlene Jesus Soares, and Filho José Rodrigues Farias. 2017. "The Internet of Things Sensors Technologies and Their Applications for Complex Engineering Projects: A Digital Construction Site Framework." *Brazilian Journal of Operations & Production Management* 14 (4). https://doi.org/10.14488/BJOPM.2017.v14.n4.a12.

Han, SangUk, Madhav Achar, SangHyun Lee, and Feniosky A. Pena-Mora. 2013. "Empirical Assessment of a Rgb-D Sensor on Motion Capture and Action Recognition for Construction Worker Monitoring." https://doi.org/10.7916/D8NS0SC9.

Han, Sanguk, and Sanghyun Lee. 2013. "A Vision-Based Motion Capture and Recognition Framework for Behavior-Based Safety Management." *Automation in Construction* 35: 131-141. https://doi.org/10.1016/j.autcon.2013.05.001.

Heller, Alfred, and Christian Orthmann. 2014. "Wireless Technologies for the Construction Sector—Requirements, Energy and Cost Efficiencies." *Energy & Buildings* 73 (C): 212-216. https://doi.org/10.1016/j.enbuild.2013.12.019.

Heng, Li, Dong Shuang, Martin Skitmore, He Qinghua, and Yin Qin. 2016. "Intrusion Warning and Assessment Method for Site Safety Enhancement." *Safety Science* 84: 97-107. https://doi.org/https://doi.org/10.1016/j.ssci.2015.12.004.

Hong, Ying, Samad Sepasgozar, A. Ahmadian, and Ali Akbarnezhad. 2016. "Factors Influencing Bim Adoption in Small and Medium Sized Construction Organizations." *ISARC. Proceedings of the International Symposium on Automation and Robotics in Construction* 33: 1-1.

Hwang, Seokyon. 2012. "Ultra-Wide Band Technology Experiments for Real-Time Prevention of Tower Crane Collisions." *Automation in Construction* 22: 545-553. https://doi.org/10.1016/j.autcon.2011.11.015.

Hwang, Sungjoo, Houtan Jebelli, Byungjoo Choi, Minji Choi, and Sanghyun Lee. 2018. "Measuring Workers' Emotional State During Construction Tasks Using Wearable Eeg." *Journal of Construction Engineering and Management* 144 (7). https://doi.org/10.1061/(ASCE)CO.1943-7862.0001506.

Hwang, Sungjoo, and Sanghyun Lee. 2017. "Wristband-Type Wearable Health Devices to Measure Construction Workers' Physical Demands." *Automation in Construction* 83: 330-340. https://doi.org/10.1016/j.autcon.2017.06.003.

Iacobucci, Dawn. 2010. "Structural Equations Modeling: Fit Indices, Sample Size, and Advanced Topics." *Journal of consumer psychology* 20 (1): 90-98.

Ibrahim, Magdy, and Osama Moselhi. 2014. "Wireless Sensor Networks Configurations for Applications in Construction." *Procedia Engineering* 85 (C): 260-273. https://doi.org/10.1016/j.proeng.2014.10.551.

Ikediashi, Dubem Isaac, and Amaka Chinweude Ogwueleka. 2016. "Assessing the Use of Ict Systems and Their Impact on Construction Project Performance in the Nigerian Construction Industry." *Journal of Engineering, Design and Technology*.

Irene Vasilachis de, Gialdino. 2009. "Ontological and Epistemological Foundations of Qualitative Research." *Forum: Qualitative Social Research* 10 (2).

Jacobs, Jesse V., Lawrence J. Hettinger, Yueng-Hsiang Huang, Susan Jeffries, Mary F. Lesch, Lucinda A. Simmons, Santosh K. Verma, and Joanna L. Willetts. 2019. "Employee Acceptance of Wearable Technology in the Workplace." *Appl Ergon* 78: 148-156. https://doi.org/10.1016/j.apergo.2019.03.003.

Jebelli, Houtan, Changbum R. Ahn, and Terry L. Stentz. 2016. "Comprehensive Fall-Risk Assessment of Construction Workers Using Inertial Measurement Units: Validation of the Gait-Stability Metric to Assess the Fall Risk of Iron Workers." *Journal of Computing in Civil Engineering* 30 (3): 4015034. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000511.

Jebelli, Houtan, Sungjoo Hwang, and SangHyun Lee. 2017. "Feasibility of Field Measurement of Construction Workers' Valence Using a Wearable Eeg Device." In *Computing in Civil Engineering 2017* ed., edited 99-106.

Jebelli, Houtan, Sungjoo Hwang, and SangHyun Lee. 2018a. "Eeg-Based Workers' Stress Recognition at Construction Sites." *Automation in construction* 93: 315-324. https://doi.org/10.1016/j.autcon.2018.05.027.

Jebelli, Houtan, Sungjoo Hwang, and SangHyun Lee. 2018b. "Eeg Signal-Processing Framework to Obtain High-Quality Brain Waves from an Off-the-Shelf Wearable Eeg Device." *Journal of Computing in Civil Engineering* 32 (1): 04017070.

Jha, N. K. 2008. *Research Methodology / N.K. Jha*. 1st ed.. ed. Chandigarh: Chandigarh : Abhishek Publications.

Kamišalić, Aida, Jr Iztok Fister, Muhamed Turkanović, and Sašo Karakatič. 2018. "Sensors and Functionalities of Non-Invasive Wrist-Wearable Devices: A Review." *Sensors (Basel)* 18 (6): 1714. https://doi.org/10.3390/s18061714.

Kanan, Riad, Obaidallah Elhassan, and Rofaida Bensalem. 2018. "An Iot-Based Autonomous System for Workers' Safety in Construction Sites with Real-Time Alarming, Monitoring, and Positioning Strategies." *Automation in Construction* 88: 73-86. https://doi.org/https://doi.org/10.1016/j.autcon.2017.12.033.

Kelm, Agnes, Lars Laußat, Anica Meins-Becker, Daniel Platz, Mohammad J. Khazaee, Aaron M. Costin, Manfred Helmus, and Jochen Teizer. 2013. "Mobile Passive Radio Frequency Identification (Rfid) Portal for Automated and Rapid Control of Personal Protective Equipment (Ppe) on Construction Sites." *Automation in Construction* 36 (C): 38-52. https://doi.org/10.1016/j.autcon.2013.08.009.

Khoury, Hiam M., and Vineet R. Kamat. 2009. "Evaluation of Position Tracking Technologies for User Localization in Indoor Construction Environments." *Automation in Construction* 18 (4): 444-457. https://doi.org/10.1016/j.autcon.2008.10.011.

Kim, Changyoon, Hyoungkwan Kim, Jeoungpil Ryu, and Changwan Kim. 2011. "Ubiquitous Sensor Network for Construction Material Monitoring." *Journal of Construction Engineering and Management* 137 (2): 158-165. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000257.

Kim, Min-Koo, Jack C. P. Cheng, Hoon Sohn, and Chih-Chen Chang. 2015. "A Framework for Dimensional and Surface Quality Assessment of Precast Concrete Elements Using Bim and 3d Laser Scanning." *Automation in Construction* 49: 225-238. https://doi.org/https://doi.org/10.1016/j.autcon.2014.07.010.

Klenke, Karin author. 2016. *Qualitative Research in the Study of Leadership / Karin Klenke*

with Guest Chapters by Suzanne Martin, J. Randall Wallace. Edited by Suzanne author Martin and J. Randall author Wallace. 2nd ed.. ed: Bingley, [England] : Emerald.

Kline, Rex B. 2015. *Principles and Practice of Structural Equation Modeling*: Guilford publications.

Kline, Rex B. 2010. *Principles and Practice of Structural Equation Modeling / Rex B. Kline*. 3rd ed.. ed. New York: New York : Guilford Press.

Ko, Chien-Ho. 2010. "Rfid 3d Location Sensing Algorithms." *Automation in Construction* 19 (5): 588-595. https://doi.org/https://doi.org/10.1016/j.autcon.2010.02.003.

Kraazt, J., A. Sanchez, and Keith D. Hampson. 2014. "Digital Modeling, Integrated Project Delivery and Industry Transformation: An Australian Case Study."

Kwang-Pyo, Lee, Lee Hyun-Soo, Park Moonseo, Kim Hyunsoo, and Han Sangwon. 2014. "A Real-Time Location-Based Construction Labor Safety Management System." *Journal of Civil Engineering and Management* 20 (5). https://doi.org/10.3846/13923730.2013.802728.

Lam, Terence Y. M., and Njavwa Siwingwa. 2017. "Risk Management and Contingency Sum of Construction Projects." *Journal of Financial Management of Property and Construction* 22 (3): 237-251. https://doi.org/10.1108/JFMPC-10-2016-0047.

Lee, Ghang, Joonbeom Cho, Sungil Ham, Taekwan Lee, Gaang Lee, Seok-Heon Yun, and Hyung-Jun Yang. 2012. "A Bim- and Sensor-Based Tower Crane Navigation System for Blind Lifts." *Automation in Construction* 26 (C): 1-10. https://doi.org/10.1016/j.autcon.2012.05.002.

Lee, Han-Seung, Myoung-Won Cho, Hyun-Min Yang, Sung-Bok Lee, and Won-Jun Park. 2014. "Curing Management of Early-Age Concrete at Construction Site Using Integrated Wireless Sensors." *Journal of Advanced Concrete Technology* 12 (3): 91-100. https://doi.org/10.3151/jact.12.91.

Lee, Nick, and Ian Lings. 2008. *Doing Business Research: A Guide to Theory and Practice*: Sage.

Lee, Seulki, Jungho Yu, and David Jeong. 2015. "Bim Acceptance Model in Construction Organizations." *Journal of Management in Engineering* 31 (3): 04014048. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000252.

Lee, Wonil, Ken-Yu Lin, Edmund Seto, and Giovanni C. Migliaccio. 2017. "Wearable Sensors for Monitoring on-Duty and Off-Duty Worker Physiological Status and Activities in Construction." *Automation in Construction* 83: 341-353. https://doi.org/10.1016/j.autcon.2017.06.012.

Li, Heng, Greg Chan, Johnny Kwok Wai Wong, and Martin Skitmore. 2016. "Real-Time Locating Systems Applications in Construction." *Automation in Construction* 63: 37-47. https://doi.org/https://doi.org/10.1016/j.autcon.2015.12.001.

Li, Jian-guo, and Kai Zhan. 2018. "Intelligent Mining Technology for an Underground Metal Mine Based on Unmanned Equipment." *Engineering* 4 (3): 381-391. https://doi.org/https://doi.org/10.1016/j.eng.2018.05.013.

Li, Terry H. Y., S. Thomas Ng, and Martin Skitmore. 2013. "Evaluating Stakeholder Satisfaction During Public Participation in Major Infrastructure and Construction Projects: A Fuzzy Approach." *Automation in Construction* 29: 123-135. https://doi.org/https://doi.org/10.1016/j.autcon.2012.09.007.

Liu, Junying, Xianbo Zhao, and Yuan Li. 2017. "Exploring the Factors Inducing Contractors' Unethical Behavior: Case of China." *Journal of Professional Issues in Engineering Education and Practice* 143 (3): 04016023. https://doi.org/10.1061/(ASCE)EI.1943-5541.0000316.

Liu, Zhen, Mohamed Osmani, Peter Demian, and Andrew Baldwin. 2015. "A Bim-Aided Construction Waste Minimisation Framework." *Automation in Construction* 59: 1-23. https://doi.org/https://doi.org/10.1016/j.autcon.2015.07.020.

Love, Peter E. D., and Zahir Irani. 2004. "An Exploratory Study of Information Technology Evaluation and Benefits Management Practices of Smes in the Construction Industry." *Information & Management* 42 (1): 227-242. https://doi.org/10.1016/j.im.2003.12.011.

Love, Peter E. D., Zahir Irani, and David J. Edwards. 2004. "Industry-Centric Benchmarking of Information Technology Benefits, Costs and Risks for Small-to-Medium Sized Enterprises in Construction." *Automation in Construction* 13 (4): 507-524. https://doi.org/10.1016/j.autcon.2004.02.002.

Lowry, Paul Benjamin, and James Gaskin. 2014. "Partial Least Squares (Pls) Structural Equation Modeling (Sem) for Building and Testing Behavioral Causal Theory: When to Choose It and How to Use It." *IEEE Transactions on Professional Communication* 57 (2): 123-146. https://doi.org/10.1109/TPC.2014.2312452.

Lu, Weisheng, George Q. Huang, and Heng Li. 2011. "Scenarios for Applying Rfid Technology in Construction Project Management." *Automation in Construction* 20 (2): 101-106. https://doi.org/https://doi.org/10.1016/j.autcon.2010.09.007.

Luo, X., H. Li, T. Huang, and M. Skitmore. 2016. "Quantifying Hazard Exposure Using Real-Time Location Data of Construction Workforce and Equipment." *Journal of Construction Engineering and Management* 142 (8). https://doi.org/10.1061/(ASCE)CO.1943-7862.0001139.

Maalek, R., and F. Sadeghpour. 2013. "Accuracy Assessment of Ultra-Wide Band Technology in Tracking Static Resources in Indoor Construction Scenarios." *Automation in Construction* 30: 170-183. https://doi.org/https://doi.org/10.1016/j.autcon.2012.10.005.

Macarulla, Marcel, Nuria Forcada, Miquel Casals, Marta Gangolells, Alba Fuertes, and Xavier Roca. 2013. "Standardizing Housing Defects: Classification, Validation, and Benefits." *Journal of Construction Engineering and Management* 139 (8): 968-976. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000669.

Majrouhi Sardroud, Javad. 2012. "Influence of Rfid Technology on Automated Management of Construction Materials and Components." *Scientia Iranica* 19 (3): 381-392. https://doi.org/https://doi.org/10.1016/j.scient.2012.02.023.

Mao, Chao, Yuhan Gao, Guiwen Liu, Markus König, and Jingke Hong. 2018. "Using Wearable Devices to Explore the Relationship among the Work Productivity, Psychological State, and Physical Status of Construction Workers." Paper presented at the *ISARC. Proceedings of the International Symposium on Automation and Robotics in Construction*, *2018*: IAARC Publications.

Marks, Eric Daniel, and Jochen Teizer. 2013. "Method for Testing Proximity Detection and Alert Technology for Safe Construction Equipment Operation." *Construction Management and Economics* 31 (6): 636-646. https://doi.org/10.1080/01446193.2013.783705.

Martínez-Rojas, María, Nicolás Marín, and M. Amparo Vila. 2016. "The Role of Information Technologies to Address Data Handling in Construction Project Management."

Journal of Computing in Civil Engineering 30 (4). https://doi.org/10.1061/(ASCE)CP.1943-5487.0000538.

Maxwell, Joseph A. 2004. "Using Qualitative Methods for Causal Explanation." *Field Methods* 16 (3): 243-264. https://doi.org/10.1177/1525822X04266831.

Mettler, Tobias, and Jochen Wulf. 2018. "Physiolytics at the Workplace: Affordances and Constraints of Wearables Use from an Employee's Perspective." *Information systems journal (Oxford, England)* 29 (1): 245-273. https://doi.org/10.1111/isj.12205.

Miller, George A. 1956. "The Magical Number Seven, Plus or Minus Two: Some Limits on Our Capacity for Processing Information." *Psychol Rev* 63 (2): 81-97. https://doi.org/10.1037/h0043158.

Miller, Mark L., and Leonhard E. Bernold. 1991. "Sensor-Integrated Nailing for Building Construction." *Journal of Construction Engineering and Management* 117 (2): 213-225. https://doi.org/10.1061/(ASCE)0733-9364(1991)117:2(213).

Mir, Raza, and Andrew Watson. 2000. "Strategic Management and the Philosophy of Science: The Case for a Constructivist Methodology." *Strategic management journal* 21 (9): 941-953. https://doi.org/10.1002/1097-0266(200009)21:9<941::AID-SMJ141>3.0.CO

2-D.

Mitropoulos, Panagiotis, and C. B. Tatum. 1999. "Technology Adoption Decisions in Construction Organizations." *Journal of Construction Engineering and Management* 125 (5): 330-338. https://doi.org/10.1061/(ASCE)0733-9364(1999)125:5(330).

Mitropoulos, Panagiotis, and C. B. Tatum. 2000. "Forces Driving Adoption of New Information Technologies." *Journal of Construction Engineering and Management* 126 (5): 340-348. https://doi.org/10.1061/(ASCE)0733-9364(2000)126:5(340).

Mneymneh, Bahaa Eddine, Mohamad Abbas, and Hiam Khoury. 2017. "Automated Hardhat Detection for Construction Safety Applications." *Procedia Engineering* 196: 895-902. https://doi.org/https://doi.org/10.1016/j.proeng.2017.08.022.

Molwus, Jurbe J, Bilge Erdogan, and Stephen O Ogunlana. 2013. "Sample Size and Model Fit Indices for Structural Equation Modelling (Sem): The Case of Construction Management Research." In *Iccrem 2013: Construction and Operation in the Context of Sustainability* ed., edited 338-347.

Molwus, Jurbe Joseph, Bilge Erdogan, and Stephen Ogunlana. 2017. "Using Structural Equation Modelling (Sem) to Understand the Relationships among Critical Success Factors (Csfs) for Stakeholder Management in Construction." *Engineering, Construction and Architectural Management* 24 (3): 426-450. https://doi.org/10.1108/ECAM-10-2015-0161.

Moon, Sungkon, Shouzhi Xu, Lei Hou, Changzhi Wu, Xiangyu Wang, and Vivian W. Y. Tam. 2018. "Rfid-Aided Tracking System to Improve Work Efficiency of Scaffold Supplier: Stock Management in Australasian Supply Chain." *Journal of Construction Engineering and Management* 144 (2): 4017115. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001432.

Moon, Sungkon, Payam R. Zekavat, and Leonhard E. Bernold. 2017. "Dynamic Quality Control of Process Resource to Improve Concrete Supply Chain." *Journal of Construction Engineering and Management* 143 (5). https://doi.org/10.1061/(ASCE)CO.1943-7862.0001270.

Moselhi, Osama, Hassan Bardareh, and Zhenhua Zhu. 2020. "Automated Data Acquisition in Construction with Remote Sensing Technologies." *Applied Sciences* 10 (2846): 2846. https://doi.org/10.3390/app10082846.

Mukhopadhyay, Subhas Chandra. 2011. *New Developments in Sensing Technology for Structural Health Monitoring / Edited by Subhas Chandra Mukhopadhyay*. Edited by SpringerLink. Berlin, Heidelberg: Berlin, Heidelberg : Springer Berlin Heidelberg.

Mukhopadhyay, Subhas Chandra. 2015. "Wearable Sensors for Human Activity Monitoring: A Review." *IEEE Sensors Journal* 15 (3): 1321-1330. https://doi.org/10.1109/JSEN.2014.2370945.

Nath, Nipun D., Reza Akhavian, and Amir H. Behzadan. 2017. "Ergonomic Analysis of Construction Worker's Body Postures Using Wearable Mobile Sensors." *Applied Ergonomics* 62: 107-117. https://doi.org/10.1016/j.apergo.2017.02.007.

Naticchia, B., G. Fava, A. Carbonari, and E. Quaquero. 2014. "Preliminary Tests on a Wireless Sensor Network for Pervasive Dust Monitoring in Construction Sites." *Open Environmental Engineering Journal* 7 (1): 10-18. https://doi.org/10.2174/1874829501407010010.

Naticchia, Berardo, Massimo Vaccarini, and Alessandro Carbonari. 2013. "A Monitoring System for Real-Time Interference Control on Large Construction Sites." *Automation in Construction* 29: 148-160. https://doi.org/https://doi.org/10.1016/j.autcon.2012.09.016.

Nnaji, Chukwuma, John Gambatese, Ali Karakhan, and Chinweike Eseonu. 2019. "Influential Safety Technology Adoption Predictors in Construction." *Engineering, Construction and Architectural Management* 26 (11): 2655-2681. https://doi.org/10.1108/ECAM-09-2018-0381.

Novikov, Alexander M., and Dmitry A. Novikov. 2013. *Research Methodology*. 1 ed. Vol. 2, *From Philosophy of Science to Research Design*.

Nunnally, Jum C. 1978. *Psychometric Theory*. 2d ed.. ed. New York: New York : McGraw-Hill.

Odubiyi, T. B., C. O. Aigbavboa, and W. D. Thwala. 2019. "Information and Communication Technology Application Challenges in the Construction Industry: A Narrative Review." *IOP Conference Series: Materials Science and Engineering* 640 (1): 012025. https://doi.org/10.1088/1757-899X/640/1/012025.

Olaniyan, Rasaq. 2019. 'Barriers to Technology Adoption among Construction Project Managers in Nigeria.' ProQuest Dissertations Publishing.

Olatunji, Oluwole, and A. Akanmu. 2014. 'An Adaptive Cyber-Physical System's Approach to Construction Progress Monitoring and Control.'

Othman, Idris, Zain Hashim, Hisham Mohamad, and Madzlan Napiah. 2018. "The Framework for Effective Human Resource Management at Construction Site." *MATEC Web of Conferences* 203: 02002. https://doi.org/10.1051/matecconf/201820302002.

Ozorhon, Beliz, and Kutluhan Oral. 2017. "Drivers of Innovation in Construction Projects." *Journal of Construction Engineering and Management* 143 (4). https://doi.org/10.1061/(ASCE)CO.1943-7862.0001234.

Ozumba, Aghaegbuna Obinna, Udechukwu Ojiako, Winston Shakantu, Alasdair Marshall, and Maxwell Chipulu. 2019. "Process Need Areas and Technology Adoption in Construction Site Management." *Journal of construction in developing countries* 24 (2): 123-155. https://doi.org/10.21315/jcdc2019.24.2.6.

Park, Man-Woo, Christian Koch, and Ioannis Brilakis. 2012. "Three-Dimensional Tracking of Construction Resources Using an on-Site Camera System." *Journal of Computing in Civil Engineering* 26 (4): 541-549. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000168.

Park, Man-Woo, Atefe Makhmalbaf, and Ioannis Brilakis. 2011. "Comparative Study of Vision Tracking Methods for Tracking of Construction Site Resources." *Automation in Construction* 20 (7): 905-915. https://doi.org/https://doi.org/10.1016/j.autcon.2011.03.007.

Patterson, Michael E, and Daniel R Williams. 1998. "Paradigms and Problems: The Practice of Social Science in Natural Resource Management."

Rahnamayiezekavat, Payam, M. Mortaheb, S. Han, and L. Bernold. 2014. "Comparative Study of Gps-Integrated Concrete Supply Management Using Discrete Event Simulation."

Ray, Soumitry J., and Jochen Teizer. 2012. "Real-Time Construction Worker Posture Analysis for Ergonomics Training." *Advanced Engineering Informatics* 26 (2): 439-455. https://doi.org/10.1016/j.aei.2012.02.011.

Razavi, Saiedeh N., and Carl T. Haas. 2011. "Using Reference Rfid Tags for Calibrating the Estimated Locations of Construction Materials." *Automation in Construction* 20 (6): 677-685. https://doi.org/10.1016/j.autcon.2010.12.009.

Razavi, Saiedeh N., and Carl T. Haas. 2012. "Reliability-Based Hybrid Data Fusion Method for Adaptive Location Estimation in Construction." *Journal of Computing in Civil Engineering* 26 (1): 1-10. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000101.

Razavi, Saiedeh N., Ali Montaser, and Osama Moselhi. 2012. "Rfid Deployment Protocols for Indoor Construction." *Construction Innovation* 12 (2): 239-258. https://doi.org/10.1108/14714171211215967.

Redwood, James, Sasha Thelning, Abbas Elmualim, and Stephen Pullen. 2017. 'The Proliferation of Ict and Digital Technology Systems and Their Influence on the Dynamic Capabilities of Construction Firms.'

Ren, Z., C. J. Anumba, and J. Tah. 2011. "Rfid-Facilitated Construction Materials Management (Rfid-Cmm) - a Case Study of Water-Supply Project." *Adv. Eng. Inform.* 25 (2): 198-207. https://doi.org/10.1016/j.aei.2010.02.002.

Rigdon, Edward E. 2016. "Choosing Pls Path Modeling as Analytical Method in European Management Research: A Realist Perspective." *European Management Journal* 34 (6): 598-605. https://doi.org/10.1016/j.emj.2016.05.006.

Robert-Lachaine, Xavier, Hakim Mecheri, Christian Larue, and André Plamondon. 2017. "Accuracy and Repeatability of Single-Pose Calibration of Inertial Measurement Units for Whole-Body Motion Analysis." *Gait Posture* 54: 80-86. https://doi.org/10.1016/j.gaitpost.2017.02.029.

Rogers, J., Heap Yih Chong, and C. Preece. 2015. "Adoption of Building Information Modelling Technology (Bim): Perspectives from Malaysian Engineering Consulting Services Firms."

Rossi, Andrea, Yanet Vila, Federico Lusiani, Ludovico Barsotti, Luca Sani, Pierfrancesco Ceccarelli, and Michele Lanzetta. 2019. "Embedded Smart Sensor Device in Construction Site Machinery." *Computers in Industry* 108: 12-20. https://doi.org/10.1016/j.compind.2019.02.008.

Safe Work Australia. February 2015. 'Work Health and Safety Perceptions: Construction Industry.' edited by SAFE WORK AUSTRALIA.

Safe Work Australia. May 2015. 'Construction Industry Profile.' edited by Safe Work Australia.

Sardroud, Javad Majrouhi 2014. "Perceptions of Automated Data Collection Technology Use in the Construction Industry." *Journal of Civil Engineering and Management* 21 (1). https://doi.org/10.3846/13923730.2013.802734.

Sargent, Kimberley, Paul Hyland, and Sukanlaya Sawang. 2012. "Factors Influencing the Adoption of Information Technology in a Construction Business." *Australasian Journal of Construction Economics and Building, The* 12 (2): 72-86. https://doi.org/10.5130/ajceb.v12i2.2448.

Saunders, Mark. 2012. *Research Methods for Business Students / Mark Saunders, Philip Lewis, Adrian Thornhill*. Edited by Philip Lewis and Adrian Thornhill. 6th ed.. ed. Harlow, England

New York: Harlow, England

New York : Pearson.

Saunders, Mark, P. Lewis, and A. Thornhill. 2009. "Understanding Research Philosophies and Approaches." *Research Methods for Business Students* 4: 106-135.

Saunders, Mark N. K., Philip Lewis, and Adrian Thornhill. 2015. *Research Methods for Business Students: 7. Ed*. Harlow u.a: Harlow u.a: Pearson.

Schall, Mark C., Nathan B. Fethke, Howard Chen, Sakiko Oyama, and David I. Douphrate. 2015. "Accuracy and Repeatability of an Inertial Measurement Unit System for Field-Based Occupational Studies." *Ergonomics* 59 (4): 591-602. https://doi.org/10.1080/00140139.2015.1079335.

Schall, Mark C., Richard F. Sesek, and Lora A. Cavuoto. 2018. "Barriers to the Adoption of Wearable Sensors in the Workplace: A Survey of Occupational Safety and Health Professionals." *Hum Factors* 60 (3): 351-362. https://doi.org/10.1177/0018720817753907.

Sepasgozaar, Samad M. E., Sara Shirowzhan, and Cynthia Wang. 2017. 'A Scanner Technology Acceptance Model for Construction Projects.'

Sepasgozar, Samad M. E. , and Steven Davis. 2018. "Construction Technology Adoption Cube: An Investigation on Process, Factors, Barriers, Drivers and Decision Makers Using Nvivo and Ahp Analysis." *Buildings* 8 (6): 74. https://doi.org/10.3390/buildings8060074.

Sepasgozar, Samad M. E., Steven R. Davis, Heng Li, and Xianrui Luo. 2018. "Modeling the Implementation Process for New Construction Technologies: Thematic Analysis Based on Australian and U.S. Practices." *Journal of Management in Engineering* 34 (3). https://doi.org/10.1061/(ASCE)ME.1943-5479.0000608.

Sepasgozar, Samad M. E., and Martin Loosemore. 2017. "The Role of Customers and Vendors in Modern Construction Equipment Technology Diffusion." *Engineering, Construction and Architectural Management* 24 (6): 1203-1221. https://doi.org/10.1108/ECAM-06-2016-0149.

Sepasgozar, Samad M. E., Martin Loosemore, and Steven R. Davis. 2016. "Conceptualising Information and Equipment Technology Adoption in Construction." *Engineering, Construction and Architectural Management* 23 (2): 158-176. https://doi.org/10.1108/ECAM-05-2015-0083.

Sepasgozar, Samad ME. 2015. "Technology Adoption in Construction." The University of New South Wales Sydney, Australia.

Sepasgozar, Samad ME, and Leonhard E Bernold. 2013a. "Factors Influencing the Decision of Technology Adoption in Construction." In *Icsdec 2012: Developing the Frontier of Sustainable Design, Engineering, and Construction* ed., edited 654-661.

Sepasgozar, Samad ME, and Steven Davis. 2014. "Diffusion Pattern Recognition of Technology Vendors in Construction." Paper presented at the *Construction Research Congress 2014: Construction in a Global Network*, *2014*.

Sepasgozar, SM, and Leonhard E Bernold. 2013b. "Factors Influencing Construction Technology Adoption." Paper presented at the *19th CIB World Building Congress, Brisbane*, *2013b*.

Shahi, Arash, Afrooz Aryan, Jeffrey S. West, Carl T. Haas, and Ralph C. G. Haas. 2012. "Deterioration of Uwb Positioning During Construction." *Automation in Construction* 24: 72-80. https://doi.org/10.1016/j.autcon.2012.02.009.

Shen, Xuesong, and Ming Lu. 2012. "A Framework for Indoor Construction Resources Tracking by Applying Wireless Sensor Networks 1 1 This Paper Is One of a Selection of Papers in This Special Issue on Construction Engineering and Management." *Canadian Journal of Civil Engineering* 39 (9): 1083-1088. https://doi.org/10.1139/L2012-094.

Shi, Qian, Xue Ding, Jian Zuo, and George Zillante. 2016. "Mobile Internet Based Construction Supply Chain Management: A Critical Review." *Automation in Construction* 72: 143-154. https://doi.org/10.1016/j.autcon.2016.08.020.

Shin, Jae Min, Sang Yong Kim, Gwang Hee Kim, Min Gu Jung, and Dae Woong Shin. 2014. "Ubiquitous Sensor Network for Construction Site Monitoring." *Advanced Materials Research* 919: 388-391. https://doi.org/10.4028/www.scientific.net/AMR.919-921.388.

Shin, Tae-Hong, Sangyoon Chin, Su-Won Yoon, and Soon-Wook Kwon. 2011. "A Service-Oriented Integrated Information Framework for Rfid/Wsn-Based Intelligent Construction Supply Chain Management." *Automation in Construction* 20 (6): 706-715. https://doi.org/10.1016/j.autcon.2010.12.002.

Shou, Wenchi, Jun Wang, Peng Wu, and Xiangyu Wang. 2019. "Value Adding and Non-Value Adding Activities in Turnaround Maintenance Process: Classification, Validation, and Benefits." *Production planning & control* 31 (1): 60-77. https://doi.org/10.1080/09537287.2019.1629038.

Siddiqui, Hassaan. 2014. "Uwb Rtls for Construction Equipment Localization: Experimental Performance Analysis and Fusion with Video Data." Concordia University.

Siddiqui, Hassaan, Faridaddin Vahdatikhaki, and Amin Hammad. 2019. "Case Study on Application of Wireless Ultra-Wideband Technology for Tracking Equipment on a Congested Site." *Journal of information technology in construction* 24: 167-187.

Siu, Ming-Fung, Ming Lu, and Simaan AbouRizk. 2013. "Combining Photogrammetry and Robotic Total Stations to Obtain Dimensional Measurements of Temporary Facilities in Construction Field." *Visualization in Engineering* 1 (1): 1-15. https://doi.org/10.1186/2213-7459-1-4.

Skibniewski, Mirosław J., and Won-Suk Jang. 2009. "Simulation of Accuracy Performance for Wireless Sensor-Based Construction Asset Tracking." *Computer-Aided Civil and Infrastructure Engineering* 24 (5): 335-345. https://doi.org/10.1111/j.1467-8667.2009.00592.x.

Smaoui, Nour, Kyungki Kim, Omprakash Gnawali, Young-Joo Lee, and Wonho Suh. 2018. "Respirable Dust Monitoring in Construction Sites and Visualization in Building Information Modeling Using Real-Time Sensor Data." *Sensors and Materials* 30 (8): 1775. https://doi.org/10.18494/SAM.2018.1871.

Soleimanifar, Meimanat. 2011. 'Intellisensornet: A Positioning Technique Integrating Wireless Sensor Networks and Artificial Neural Networks for Critical Construction Resource Tracking.' edited by Ming Lu: ProQuest Dissertations Publishing.

Soltanmohammadlou, Nazi, Sanaz Sadeghi, Carol K. H. Hon, and Fariba Mokhtarpour-Khanghah. 2019. "Real-Time Locating Systems and Safety in Construction Sites: A Literature Review." *Safety Science* 117: 229-242. https://doi.org/https://doi.org/10.1016/j.ssci.2019.04.025.

Son, Hyojoo, Yoora Park, Changwan Kim, and Jui-Sheng Chou. 2012. "Toward an Understanding of Construction Professionals' Acceptance of Mobile Computing Devices in South Korea: An Extension of the Technology Acceptance Model." *Automation in construction* 28: 82-90. https://doi.org/10.1016/j.autcon.2012.07.002.

Song, Lingguang, Tanvir Mohammed, David Stayshich, and Neil Eldin. 2015. "A Cost Effective Material Tracking and Locating Solution for Material Laydown Yard." *Procedia Engineering* 123 (C): 538-545. https://doi.org/10.1016/j.proeng.2015.10.106.

Song, Zhan-Pu, Dan Zhang, Bin Shi, Shen-En Chen, and Meng-Fen Shen. 2017. "Integrated Distributed Fiber Optic Sensing Technology-Based Structural Monitoring of the Pound Lock." *Structural Control and Health Monitoring* 24 (7): n/a-n/a. https://doi.org/10.1002/stc.1954.

Spillane, John P., and Lukumon O. Oyedele. 2017. "Effective Material Logistics in Urban Construction Sites: A Structural Equation Model." *Construction Innovation* 17 (4): 406-428. https://doi.org/10.1108/CI-11-2015-0063.

Spillane, John P., Lukumon O. Oyedele, Jason Von Meding, Ashwini Konanahalli, Babatunde E. Jaiyeoba, and Iyabo K. Tijani. 2011. "Challenges of Uk/Irish Contractors Regarding Material Management and Logistics in Confined Site Construction." *International Journal of Construction Supply Chain Management* 1 (1): 25-42. https://doi.org/10.14424/ijcscm101011-25-42.

Stewart, R. A., S. Mohamed, and M. Marosszeky. 2004. "An Empirical Investigation into the Link between Information Technology Implementation Barriers and Coping Strategies in the Australian Construction Industry." *Construction Innovation* 4 (3): 155-171. https://doi.org/10.1108/14714170410815079.

Sun, Chengshuang, Fan Jiang, and Shaohua Jiang. 2013. "Research on Rfid Applications in Construction Industry." *Journal of Networks* 8 (5): 1221-1221.

Sung Hun, Kim, Wang Changwon, Min Se Dong, and Lee Seung Hyun. 2018. "Safety Helmet Wearing Management System for Construction Workers Using Three-Axis Accelerometer Sensor." *Applied Sciences* 8 (12): 2400. https://doi.org/10.3390/app8122400.

Sweis, Ghaleb J., Rateb J. Sweis, Muhannad A. Al-Shboul, and Ghadeer A. Al-Dweik. 2015. "The Impact of Information Technology (It) Adoption on the Quality of Construction Projects: The Case of Jordan." *International Journal of Information Technology*

Project Management (IJITPM) 6 (3): 26-40. https://doi.org/10.4018/IJITPM.2015070102.

Taherdoost, Hamed. 2017. "Determining Sample Size; How to Calculate Survey Sample Size."

Tam, Vivian, Khoa Le, and Jiayuan Wang. 2017. "Examining the Existing Waste Management Practices in Construction." *International Journal of Construction Project Management* 9 (2): 99-109.

Taneja, S., B. Akinci, Jh Garrett, L. Soibelman, E. Ergen, A. Pradhan, Pb Tang et al. 2011. "Sensing and Field Data Capture for Construction and Facility Operations." *J. Constr. Eng. Manage.-ASCE* 137 (10): 870-881. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000332.

Teizer, Jochen. 2008. "3d Range Imaging Camera Sensing for Active Safety in Construction." *Journal of Information Technology in Construction (ITcon)* 13 (8): 103-117.

Teizer, Jochen, Ben S. Allread, Clare E. Fullerton, and Jimmie Hinze. 2010. "Autonomous Pro-Active Real-Time Construction Worker and Equipment Operator Proximity Safety Alert System." *Automation in Construction* 19 (5): 630-640. https://doi.org/https://doi.org/10.1016/j.autcon.2010.02.009.

Teizer, Jochen, and Tao Cheng. 2015. "Proximity Hazard Indicator for Workers-on-Foot near Miss Interactions with Construction Equipment and Geo-Referenced Hazard Areas." *Automation in Construction* 60: 58-73. https://doi.org/10.1016/j.autcon.2015.09.003.

Teizer, Jochen, Tao Cheng, and Yihai Fang. 2013. "Location Tracking and Data Visualization Technology to Advance Construction Ironworkers' Education and Training in Safety and Productivity." *Automation in Construction* 35: 53-68. https://doi.org/https://doi.org/10.1016/j.autcon.2013.03.004.

Teizer, Jochen, Manu Venugopal, and Anupreet Walia. 2008. "Ultrawideband for Automated Real-Time Three-Dimensional Location Sensing for Workforce, Equipment, and Material Positioning and Tracking." *Transportation Research Record* 2081 (2081): 56-64. https://doi.org/10.3141/2081-06.

Turkan, Yelda, Frederic Bosche, Carl T. Haas, and Ralph Haas. 2012. "Automated Progress Tracking Using 4d Schedule and 3d Sensing Technologies." *Automation in Construction* 22 (C): 414-421. https://doi.org/10.1016/j.autcon.2011.10.003.

Umer, Waleed, Heng Li, Grace Pui Yuk Szeto, and Arnold Y. L. Wong. 2017. "Low-Cost Ergonomic Intervention for Mitigating Physical and Subjective Discomfort During Manual Rebar Tying." *Journal of Construction Engineering and Management* 143 (10). https://doi.org/10.1061/(ASCE)CO.1943-7862.0001383.

Usman, Nuruddeen, and Ilias Said. 2012. "Information and Communication Technology Innovation for Construction Site Management." *American Journal of Applied Sciences* 9 (8): 1259.

Vähä, Pentti, Tapio Heikkilä, Pekka Kilpeläinen, Markku Järviluoma, and Ernesto Gambao. 2013. "Extending Automation of Building Construction — Survey on Potential Sensor Technologies and Robotic Applications." *Automation in Construction* 36: 168-178. https://doi.org/10.1016/j.autcon.2013.08.002.

Visser, Pepijn R. S., and Trevor J. M. Bench-Capon. 1998. "A Comparison of Four Ontologies for the Design of Legal Knowledge Systems." *Artificial intelligence and law* 6 (1): 27-57. https://doi.org/10.1023/A:1008251913710.

Wang, Di, Jiayu Chen, Dong Zhao, Fei Dai, Changjian Zheng, and Xiaobing Wu. 2017. "Monitoring Workers' Attention and Vigilance in Construction Activities through a Wireless and Wearable Electroencephalography System." *Automation in Construction* 82: 122-137. https://doi.org/https://doi.org/10.1016/j.autcon.2017.02.001.

Wang, Jun, and Saiedeh N. Razavi. 2016. "Low False Alarm Rate Model for Unsafe-Proximity Detection in Construction." *Journal of Computing in Civil Engineering* 30 (2). https://doi.org/10.1061/(ASCE)CP.1943-5487.0000470.

Wang, Jun, Wenchi Shou, Xiangyu Wang, and Peng Wu. 2016. "Developing and Evaluating a Framework of Total Constraint Management for Improving Workflow in Liquefied

Natural Gas Construction." *Construction Management and Economics* 34 (12): 859-874. https://doi.org/10.1080/01446193.2016.1227460.

Wang, Zhaojing, Hao Hu, and Wei Zhou. 2017. "Rfid Enabled Knowledge-Based Precast Construction Supply Chain." *Computer-aided civil and infrastructure engineering* 32 (6): 499-514. https://doi.org/10.1111/mice.12254.

Weston, Rebecca, and Paul A. Gore. 2006. "A Brief Guide to Structural Equation Modeling." *The Counseling Psychologist* 34 (5): 719-751. https://doi.org/10.1177/0011000006286345.

Woods, Megan, Trena Paulus, David P. Atkins, and Rob Macklin. 2016. "Advancing Qualitative Research Using Qualitative Data Analysis Software (Qdas)? Reviewing Potential Versus Practice in Published Studies Using Atlas.Ti and Nvivo, 1994–2013." *Social Science Computer Review* 34 (5): 597-617. https://doi.org/10.1177/0894439315596311.

Wu, Peng, Xianbo Zhao, Jessica Hedi Baller, and Xiangyu Wang. 2018. "Developing a Conceptual Framework to Improve the Implementation of 3d Printing Technology in the Construction Industry." *Architectural science review* 61 (3): 133-142. https://doi.org/10.1080/00038628.2018.1450727.

Wu, Weiwei, Huanjia Yang, David A. S. Chew, Shuang-Hua Yang, Alistair G. F. Gibb, and Qiming Li. 2010. "Towards an Autonomous Real-Time Tracking System of near-Miss Accidents on Construction Sites." *Automation in Construction* 19 (2): 134-141. https://doi.org/10.1016/j.autcon.2009.11.017.

Yang, Huanjia, David A. S. Chew, Weiwei Wu, Zhipeng Zhou, and Qiming Li. 2012. "Design and Implementation of an Identification System in Construction Site Safety for Proactive Accident Prevention." *Accident Analysis & Prevention* 48: 193-203. https://doi.org/https://doi.org/10.1016/j.aap.2011.06.017.

Yang, Kanghyeok, Changbum R. Ahn, Mehmet C. Vuran, and Hyunsoo Kim. 2017. "Collective Sensing of Workers' Gait Patterns to Identify Fall Hazards in Construction." *Automation in Construction* 82: 166-178. https://doi.org/10.1016/j.autcon.2017.04.010.

Yang, Zhihe, Yaowu Wang, and Chengshuang Sun. 2018. "Emerging Information Technology Acceptance Model for the Development of Smart Construction System." *Journal of civil engineering and management* 24 (6): 457-468. https://doi.org/10.3846/jcem.2018.5186.

Ye, X., Y. Su, and J. Han. 2014. "Structural Health Monitoring of Civil Infrastructure Using Optical Fiber Sensing Technology: A Comprehensive Review." *The Scientific World Journal* 2014. https://doi.org/10.1155/2014/652329.

Ye, X. W., Y. Q. Ni, and J. H. Yin. 2013. "Safety Monitoring of Railway Tunnel Construction Using Fbg Sensing Technology." *Advances in Structural Engineering* 16 (8): 1401-1409. https://doi.org/10.1260/1369-4332.16.8.1401.

Yi, Wen, Albert P. C. Chan, Xiangyu Wang, and Jun Wang. 2016. "Development of an Early-Warning System for Site Work in Hot and Humid Environments: A Case Study." *Automation in Construction* 62: 101-113. https://doi.org/https://doi.org/10.1016/j.autcon.2015.11.003.

Yiqiu, Tan, Wang Haipeng, Ma Shaojun, and Xu Huining. 2014. "Quality Control of Asphalt Pavement Compaction Using Fibre Bragg Grating Sensing Technology." *Construction and Building Materials* 54: 53-59. https://doi.org/10.1016/j.conbuildmat.2013.12.032.

Young, Da, C. T. Haas, P. Goodrum, and C. Caldas. 2011. "Improving Construction Supply Network Visibility by Using Automated Materials Locating and Tracking Technology." *J. Constr. Eng. Manage.-ASCE* 137 (11): 976-984. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000364.

Yu, Yantao, Hongling Guo, Qinghua Ding, Heng Li, and Martin Skitmore. 2017. "An Experimental Study of Real-Time Identification of Construction Workers' Unsafe Behaviors." *Automation in Construction* 82: 193.

Zekavat, Payam R., Sungkon Moon, and Leonhard E. Bernold. 2014a. "Performance of Short and Long Range Wireless Communication Technologies in Construction." *Automation in Construction* 47: 50-61. https://doi.org/10.1016/j.autcon.2014.07.008.

Zekavat, Payam R., Sungkon Moon, and Leonhard E. Bernold. 2014b. "Securing a Wireless Site Network to Create a Bim-Allied Work-Front." *International Journal of Advanced Robotic Systems* 11 (1). https://doi.org/10.5772/58441.

Zhang, C., A. Hammad, and S. Rodriguez. 2012. "Crane Pose Estimation Using Uwb Real-Time Location System." *Journal of Computing in Civil Engineering* 26 (5): 625-637. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000172.

Zhang, Cheng, and Amin Hammad. 2012. "Multiagent Approach for Real-Time Collision Avoidance and Path Replanning for Cranes." *Journal of Computing in Civil Engineering* 26 (6): 782-794. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000181.

Zhang, Hongjuan, Yu Wang, Xu Zhang, Dong Wang, and Baoquan Jin. 2016. "Design and Performance Analysis of an Intrinsically Safe Ultrasonic Ranging Sensor." *Sensors (Basel)* 16 (6): 867. https://doi.org/10.3390/s16060867.

Zhang, Mingyuan, Tianzhuo Cao, and Xuefeng Zhao. 2017. "Applying Sensor-Based Technology to Improve Construction Safety Management." *Sensors (Basel)* 17 (8): 1841. https://doi.org/10.3390/s17081841.

Zhou, C., and L. Y. Ding. 2017. "Safety Barrier Warning System for Underground Construction Sites Using Internet-of-Things Technologies." *Automation in Construction* 83: 372-389. https://doi.org/https://doi.org/10.1016/j.autcon.2017.07.005.

Zhou, Wei, Jennifer Whyte, and Rafael Sacks. 2012. "Construction Safety and Digital Design: A Review." *Automation in Construction* 22 (C): 102-111. https://doi.org/10.1016/j.autcon.2011.07.005.

Zhu, Zhenhua, Man-Woo Park, Christian Koch, Mohamad Soltani, Amin Hammad, and Khashayar Davari. 2016. "Predicting Movements of Onsite Workers and Mobile Equipment for Enhancing Construction Site Safety." *Automation in Construction* 68 (C): 95-101. https://doi.org/10.1016/j.autcon.2016.04.009.

APPENDICES

Appendix A Online Survey Questionnaire

Online survey questionnaire:

Sensing technologies in construction

This survey is being conducted for a PhD research project with Curtin University and investigates the application and implementation of sensing technologies in construction.
In this survey, by sensing technologies we mean those technologies involving any type of digital data collection from construction processes with the aim of improving construction safety, productivity or quality.
This survey is anonymous and all responses will remain confidential.
Please answer to all questions and submit your responses at the end of the survey. Please select "Not using at all" if you are not using or not familiar with a sensing technology mentioned here.
Your participation is very much appreciated.

Curtin University Human Research Ethics Committee (HREC) has approved this study (HRE2019-0052). Should you wish to discuss the study with someone not directly involved, in particular, any matters concerning the conduct of the study or your rights as a participant, or you wish to make a confidential complaint, you may contact the Ethics Officer on (08) 9266 9223 or the Manager, Research Integrity on (08) 9266 7093 or email hrec@curtin.edu.au.

Participant's consent:

☐ I understand that participating in this survey is voluntary and hereby give consent to take part in it.

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Part 1: General information:

Q1. Which construction sector are you working in? Please select all that apply.

- [ ] Building
- [ ] Infrastructure
- [ ] Industrial
- [ ] Other. Please specify.

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Q2. How do you describe the size of your company regarding the number of employees?

- Under 50 employees
- 50-100 employees
- 100-200 employees
- 200-500 employees
- More than 500 employees

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Q3. How do you describe the size of your company regarding its annual turnover?

- ◯ Less than $1000000
- ◯ Between 1 to 100 million dollars
- ◯ Between 100 million to 1 billion dollars
- ◯ More than 1 billion dollars

Q4. How many years of experience do you have in this industry?

- ◯ under 5 years
- ◯ 5-10 years
- ◯ 10-20 years
- ◯ More than 20 years

Q5. What position did you have in this industry for the majority of your work experience?

- ◯ Construction manager/director
- ◯ Project manager/director
- ◯ Technical manager/director
- ◯ Technology manager/director
- ◯ Other. Please specify. ______________________________

Part 2: Current implementation status of sensing technologies in construction:

Q6. How often do you use each of the following technologies in your construction projects ***to improve construction safety***?

	On a daily basis	Frequently from time to time	Only occasionally	very rarely	Not using at all
Global Positioning System (GPS)	○	○	○	○	○
Radio Frequency Identification (RFID)	○	○	○	○	○
Ultra-Wideband (UWB)	○	○	○	○	○
General packet radio service (GPRS)	○	○	○	○	○
Fiber optic sensing (FOS)	○	○	○	○	○
Pressure/Displacement sensing	○	○	○	○	○
Temperature sensing	○	○	○	○	○
Humidity sensing	○	○	○	○	○
Air quality sensing	○	○	○	○	○
Visual recording	○	○	○	○	○
3D scanning	○	○	○	○	○
Other. Please specify.	○	○	○	○	○
Other. Please specify.	○	○	○	○	○

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Q7. How often do you use each of the following technologies in your construction projects ***to improve construction productivity***?

	On a daily basis	Frequently from time to time	Only occasionally	Very rarely	Not using at all
Global Positioning System (GPS)	○	○	○	○	○
Radio Frequency Identification (RFID)	○	○	○	○	○
Ultra-Wideband (UWB)	○	○	○	○	○
General packet radio service (GPRS)	○	○	○	○	○
Bluetooth	○	○	○	○	○
Wireless local area network (WLAN)	○	○	○	○	○
Fiber Optic sensing (FOS)	○	○	○	○	○
Pressure/Displacement sensing	○	○	○	○	○
Other. Please specify.	○	○	○	○	○
Other. Please specify.	○	○	○	○	○

Q8. How often do you use each of the following technologies in your construction projects ***to improve construction quality***?

	On a daily basis	frequently from time to time	Only occasionally	very rarely	Not using at all
Fiber Optic sensing (FOS)	○	○	○	○	○
Pressure/Displacement sensing	○	○	○	○	○
Temperature sensing	○	○	○	○	○
Humidity sensing	○	○	○	○	○
Air quality sensing	○	○	○	○	○
Concrete scanning/sensing.	○	○	○	○	○
Visual recording	○	○	○	○	○
3D scanning	○	○	○	○	○
Other. Please specify.	○	○	○	○	○
Other. Please specify.	○	○	○	○	○

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Part 3: Impediments preventing/limiting the adoption of sensing technologies in construction:

Q9. What sensing technologies do you believe could be beneficial in your construction projects but are still not implemented?

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Q10. Which of the following ***financial constraints*** do you believe might have prevented or limited the adoption of sensing technologies in your company?

	Extremely likely	Very likely	Moderately likely	Slightly likely	Not likely at all
High implementation cost	○	○	○	○	○
High training cost	○	○	○	○	○
High maintenance cost	○	○	○	○	○
High data management cost	○	○	○	○	○
Other. Please specify.	○	○	○	○	○
Other. Please specify.	○	○	○	○	○

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Q11. Which of the following ***technical constraints*** do you believe might have prevented or limited the adoption of sensing technologies in your company?

	Extremely likely	Very likely	Moderately likely	Slightly likely	Not likely at all
Not safe for the construction site	○	○	○	○	○
Not accurate enough for the intended role	○	○	○	○	○
Not proved to be effective yet	○	○	○	○	○
Not adaptable with current IT infrastructure within the company	○	○	○	○	○
Hard to get technical support	○	○	○	○	○
Hard to manage too much collected data	○	○	○	○	○
Hard to get quality training	○	○	○	○	○
Hard to overcome maintenance issues	○	○	○	○	○
Other. Please specify.	○	○	○	○	○
Other. Please specify.	○	○	○	○	○

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Q12. What other constraints do you believe might have prevented or limited the adoption of sensing technologies in your company?

	Extremely likely	Very likely	Moderately likely	Slightly likely	Not likely at all
Hard to get the approval within the company/organisation	○	○	○	○	○
Low acceptance between the employees	○	○	○	○	○
invading privacy of employees	○	○	○	○	○
Power supply issues	○	○	○	○	○
Other. Please specify.	○	○	○	○	○
Other. Please specify.	○	○	○	○	○

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Part 4: Decision making criteria and motivations towards adopting new sensing technologies in construction:

Q13. How important are each of the following criteria in regards to the decision making process of adopting ***a new sensing technology*** in construction?

	Extremely important	Very important	Moderately important	Slightly important	Not important at all
Low implementation cost	○	○	○	○	○
Low maintenance cost	○	○	○	○	○
Low training cost	○	○	○	○	○
Reputation of the supplier	○	○	○	○	○
Easiness of handling data	○	○	○	○	○
Simplicity of use	○	○	○	○	○
Compatibility with current systems	○	○	○	○	○
Other. Please specify.	○	○	○	○	○
Other. Please specify.	○	○	○	○	○

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Q14. How important are each of the following motivations in regards to employing ***a new sensing technology*** during construction?

	Extremely important	Very important	Moderately important	Slightly important	Not important at all
Used by others and proved to be effective	○	○	○	○	○
Used on a trial session and proved to be effective	○	○	○	○	○
Quality technical support from the supplier for training the staff	○	○	○	○	○
Quality technical support from the supplier during the maintenance	○	○	○	○	○
Proof of effectiveness in similar projects	○	○	○	○	○
Other. Please specify.	○	○	○	○	○

Q15. Which organisation/authority do you think could help the most regarding a wider adoption of sensing technologies in construction?

○ Government and legislation authorities

○ Suppliers and sensor developers

○ Academia and researchers

○ Contractors and construction companies

○ Other. Please specify. ______________________________

Thanks for your time to take this survey. Please click on the arrow button to the right hand side of the page to submit your answers.

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Appendix B Participant Information Statement

Curtin University

PARTICIPANT INFORMATION STATEMENT

HREC Project Number:	*12099*
Project Title:	Developing a governance framework to assist with the adoption of sensing technologies in construction
Chief Investigator:	*Prof Xiangyu Wang, Head of BIM centre, Curtin University*
Student researcher:	*Mona Arabshahi*
Version Number:	*3*
Version Date:	*24/07/2020*

What is the Project About?

Traditional generic management paradigms are no longer responding for desired productivity and efficiency in modern construction projects. Consequently, there is a necessity to adopt state of the art technologies that enable project managers to modify their decisions based on unique specifications and requirements of each construction site as well as health and safety requirements affiliated with site environmental conditions. In current research, identifying project requirements will be pursued by performing semi-structured interviews and an online survey to acquire field information associated with key personnel's experiences. This attempt is expected to present a better picture in detecting project-specific issues, concerns and potential improvements.

Who is doing the Research?

- The project is being conducted by Prof Xiangyu Wang, head of the BIM centre at Curtin University, and Ms. Mona Arabshahi, PhD candidate in construction management.
- The results of this research project will be used by Mona Arabshahi to obtain a Doctor of Philosophy at Curtin University and is funded by the University.
- There will be no costs to you and you will not be paid for participating in this project.

Why am I being asked to take part and what will I have to do?

- You have been invited to participate in this research project as you are holding a key role in construction and are experienced in your position for at least 1 year.
- Participation in this research project is voluntary. Whether or not you decide to participate, your decision will not disadvantage you. Your submission of a completed consent form will be considered as an indication of your consent to participate in the current research.
- If you agree to take part in the online survey, it will only take a few minutes of your time and it is totally voluntary and confidential. The survey inquires about the extent of using sensing technologies in your field along with any concerns, barriers and motivations regarding the adoption of sensing technologies in construction.

- If you agree to being interviewed, you will be asked to take part in a semi-structured interview for up to half an hour (the total time of the interview is subject to your experience and the amount of issues and concerns you are happy to share) which comprises your technical work experiences and relevant issues and concerns you have been encountered with.
- The interview will be audio recorded. You can request a final copy of the research report by indicating this on the attached consent form.
- The interview will take place at your preferred time and schedule at a mutually convenient location.
- During the interview, we will ask you about your experiences and concerns in construction industry.
- The interview is a onetime event, only occasionally if the interviewees were happy to share more viewpoints, it might take more than one session.
- There will be no cost to you for taking part in this research and you will not be paid for taking part. We will give you up to $20 to cover your car parking while you attend interviews.
- We will make a digital audio/video recording so we can concentrate on what you have to say and not distract ourselves with taking notes. After the interview we will make a full written copy of the recording.
    - Optional Consent Future Research: We would like you to consider allowing us to send you information about future research projects. Once you receive the information it is your choice if you decide to take part or not. If you agree to this term, your contact details will remain re-identifiable for future researchers but would not be disclosed to a third party. We also would like you to consider letting us share the information we collect during this research with other researchers working in this area. Using the information you are sharing would be non-identifiable for future researches.

Are there any benefits' to being in the research project?

There may be no direct benefit to you from participating in this research. However, we appreciate that you share your viewpoints, concerns and difficulties in your position.

We hope the results of this research will allow us to:

- Add to the knowledge we have about the actual difficulties, complexities, constraints, risks and professional concerns in construction sites.
- Develop a framework to mitigate risks and enhance any aspect of construction performance.

Are there any risks, side-effects, discomforts or inconveniences from being in the research project?

- There are no foreseeable risks from this research project.
- During the research project we may find out new information about the risks and benefits of this study. If this happens we will tell you the new information and what it means to you. It may be that this new information means that you can no longer be in the study or you may choose to keep going or to leave the study. You might be asked to sign a new consent form to let us know you understand any new information we have told you.

- Apart from giving up your time, we do not expect that there will be any risks or inconveniences associated with taking part in this study.
- There will be no cost to you for taking part in this research. You are covered for the parking payments while you are attending the interview.

Who will have access to my information?

The information collected in this research will be re-identifiable (coded). This means that we will collect data that can identify you, but will then remove identifying information on any data or sample and replace it with a code when we analyse the data. Only the research team have access to the code to match your name if it is necessary to do so. Any information we collect will be treated as confidential and used only in this project unless otherwise specified. The following people will have access to the information we collect in this research: the research team and, in the event of an audit or investigation, staff from the Curtin University Office of Research and Development

Electronic data will be password-protected and hard copy data (including video or audio tapes) will be in locked storage.

The information we collect in this study will be kept under secure conditions at Curtin University for 7 years after the research is published and then it will be destroyed. The results of this research may be presented at conferences or published in professional journals. You will not be identified in any results that are published or presented.

Will you tell me the results of the research?

Upon your request, we will write to you at the end of the research and when we analysed the data and let you know the results of the research. Results will not be individual but based on all the information we collect and review as part of the research.

We intend to publish the results of this study in the students PhD thesis as well as technical journal papers.

Do I have to take part in the research project?

Taking part in a research project is voluntary. It is your choice to take part or not. You do not have to agree if you do not want to. If you decide to take part and then change your mind, that is okay, you can withdraw from the project. If you choose not to take part or start and then stop the study, it will not affect your relationship with the University, staff or colleagues. You do not have to give us a reason; just tell us that you want to stop. Please let us know you want to stop so we can make sure you are aware of any thing that needs to be done so you can withdraw safely. With your permission, if you chose to leave the study we will use any information collected unless you tell us not to.

What happens next and who can I contact about the research?

If you decide to take part in this research we will ask you to sign the consent form. By signing it is telling us that you understand what you have read and what has been discussed. Signing the consent form indicates that you agree to be in the research project and have your information used as described. Please take your time and ask any questions you have before

you decide what to do. You will be given a copy of this information and the consent form to keep.
You can send the signed consent form to "mona.arabshahi@postgrad.curtin.edu.au" or alternatively, hand it over to the interviewer before the interview.
If you had further questions please do not hesitate to contact us at: (08)92669059
For participants who decide to take part in the online survey, at the start of the questionnaire, available via the link provided, there is a checkbox to indicate you have understood the information provided here in the information sheet

Curtin University Human Research Ethics Committee (HREC) has approved this study (HRE2019-0052). Should you wish to discuss the study with someone not directly involved, in particular, any matters concerning the conduct of the study or your rights as a participant, or you wish to make a confidential complaint, you may contact the Ethics Officer on (08) 9266 9223 or the Manager, Research Integrity on (08) 9266 7093 or email hrec@curtin.edu.au.

Appendix C Participant Consent Form

Curtin University

CONSENT FORM

HREC Project Number:	*12099*
Project Title:	Developing a governance framework to assist with the adoption of sensing technologies in construction
Chief Investigator:	*Prof Xiangyu Wang, Head of BIM centre, Curtin University*
Student researcher:	*Mona Arabshahi*
Version Number:	*2*
Version Date:	*15/12/2018*

- I have read, (or had read to me in my first language), the information statement version listed above and I understand its contents.
- I believe I understand the purpose, extent and possible risks of my involvement in this project.
- I voluntarily consent to take part in this research project.
- I have had an opportunity to ask questions and I am satisfied with the answers I have received.
- I understand that this project has been approved by Curtin University Human Research Ethics Committee and will be carried out in line with the National Statement on Ethical Conduct in Human Research (2007).
- I understand that the project will be conducted as described in the information statement, a copy of which I have retained.
- I understand that I can withdraw from the project at any time and do not have to give any reason for withdrawing.

☐ I do	☐ I do not	consent to you using any data I provided before withdrawing from the study, if relevant
☐ I do	☐ I do not	consent to being audio-recorded
☐ I do	☐ I do not	consent to the storage and use of my information in future ethically-approved research projects related to this project
☐ I do	☐ I do not	consent to be contacted about future research projects that are related to this project
☐ I do	☐ I do not	need a copy of recorded audio file of the interview.
☐ I do	☐ I do not	want to be informed of the results from the current study.

Participant Name	
Participant Signature	
Date	

Declaration by researcher:
I have supplied an Information Letter and Consent Form to the participant who has signed above, and believe that they understand the purpose, extent and possible risks of their involvement in this project.

Researcher Name	
Researcher Signature	
Date	

Appendix D Questionnaire for Semi-structured Interviews

Dear Participant,

The aim of the current study is to identify value-adding information on the application of sensing technologies, by referencing to construction professionals' experiences through semi-structured interviews.

By sensing technologies, here in this research, we mean those technologies employing sensors to detect and respond to some sort of input from their environment (here the construction site) and transform it into human-readable output either stored and displayed at the location of the sensor or transmitted electronically over a network for further processing. Such real-time data could be used during any stage of construction ranging from initiation and planning to project delivery and post-delivery (maintenance).

The anticipated outcome of this research study is a framework to identify and address construction-specific impediments against widespread adoption of sensing technologies.

You have been provided with an information statement and a consent form. By signing and returning of the consent form, you have agreed to participate in this research. You can skip any question or withdraw from the interview at any time. Your identity and personal information would remain confidential.

Part 1: General information, concerns and issues.

1. What type of construction project are you working on?

2. How big is the construction site you are working at? (Regarding project value, construction area/height and number of staff)

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3. What is the position you are holding?
□ Superintendent □ Construction Manager □ Project Manager
□ Project Engineer □ Project Champion □ Other: ---

4. How many years have you been working in the current position? ---
How many years have you been working in the construction industry? ---

5. What special requirements are necessary for the position you're holding? (qualifications and experience)

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6. What are your main duties in your current role?

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7. Which types of plant and/or equipment are usually active in your construction site?

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8. What issues/difficulties are you facing in your position/on the construction site? And how these issues impose a constraint in the progress of your job/the whole project?

1

Part 2: Current status of the use of sensing technologies in construction.

9. Are you familiar with sensing technologies in your field of expertise? Which sensors are implemented on your construction site? Are these sensors essential or only beneficial to any construction process? Please specify.

10. Which issues have been resolved using such sensors? Which aspects of construction performance have been improved by sensing technologies?

11. What are the privileges of using these sensors over the similar ones or doing the work traditionally with no sensor?

12. Are there any complications or difficulties in using sensing technologies?

13. Have you ever faced a situation where these technologies were inefficient or even affected the construction performance badly?

14. Do you use any proximity detection alert system on your construction site? Please specify.

15. Do you use any sensors for tracking material/resources/workforce/equipment?

2

Part 3: Factors affecting the adoption of sensing technologies in construction.

16. Which types of sensors do you think are the most effective ones at a construction site in your field of expertise?

17. Which sensors do you think might be beneficial in your construction project but still not implemented? And what are the constraints preventing you from hiring them?

18. How did you get informed of the existence and benefits of the sensors you noted in previous question and how do you think they can be of assistance?

19. Are you or have you ever been in charge of making the decision of choosing which sensor to use on the construction site? Please specify.

20. What considerations do you take into account while nominating a sensor to be implemented on your construction site? Which factors would motivate you of hiring a new sensing technology?

21. Have you ever had the experience of requiring a sensor but could not fulfil its implementation due to any external/internal restrains? Please specify.

22. How do you usually get informed of new sensing technologies and their applicability in construction? Have you ever contacted academia or have you even been contacted by academia regarding new sensing technologies?

Part 4: Feasibility of future improvement in adopting new sensing technologies in construction.

23. Do you have any concerns regarding the use of sensing technologies on construction sites? Do they impose any risk or difficulty to your work?

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24. If you could change one thing about the current status of using sensors on construction sites, what would it be and how do you change that?

----

25. Do you have any suggestion regarding potential betterments in using sensors in construction industry?

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26. Which organisation/authority do you think could help most on the subject of motivating and improving the adoption of new sensing technologies on construction sites?

Thank you for your participation in this research study. Your contribution is much appreciated and will play an important role in progressing towards construction betterment. You will be informed of the outcome of this study upon your request on the consent form.

Kind regards,

The research team

Appendix E Evaluation and Validation Survey Questionnaire

Framework Evaluation and Validation

This survey is being conducted for a PhD research project with Curtin University to evaluate and validate a framework to assist with the adoption of sensing technologies in construction.

In this survey, by sensing technologies we mean those technologies involving any type of digital data collection from construction processes with the aim of improving construction safety, productivity or quality.

This survey is anonymous and all responses will remain confidential.

Please answer to all questions and submit your responses at the end of the survey.
Your participation is very much appreciated.

Curtin University Human Research Ethics Committee (HREC) has approved this study (HRE2019-0052). Should you wish to discuss the study with someone not directly involved, in particular, any matters concerning the conduct of the study or your rights as a participant, or you wish to make a confidential complaint, you may contact the Ethics Officer on (08) 9266 9223 or the Manager, Research Integrity on (08) 9266 7093 or email hrec@curtin.edu.au.

Participant's consent:

○ I understand that participating in this survey is voluntary and hereby give consent to take part in it.

Please briefly indicate your area of expertise and years of experience in the industry.

____

The framework for sensing technology adoption is presented here.
This framework accommodates for 6 classification of factors affecting sensing technology adoption in construction. These classifications include: Barriers, Motivations, considerations, people, cost and supplier related factors. Each classification includes different factors and affect technology adoption at some point.

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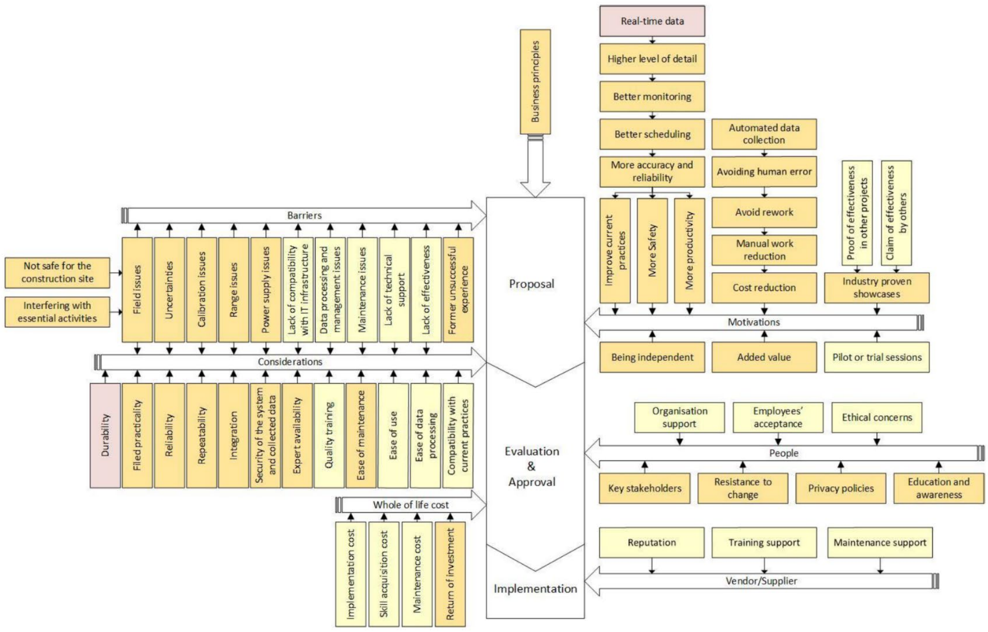

PART 1: Completeness of the framework:

1. To what extent do you agree that the framework covers all relevant factors for sensing technology adoption?

- ◯ Strongly disagree
- ◯ Disagree
- ◯ Neither agree nor disagree
- ◯ Agree
- ◯ Strongly agree

Please specify any of the following if possible. If there is no missing factor indicate: N/A

1-a. Can you point out any missing motivation to encourage construction stakeholders to adopt sensing technologies?

____

1-b. Can you point out any missing barrier limiting the adoption of sensing technologies in construction?

____

1-c. Can you point out any missing consideration for the decision making process of sensing technology adoption and implementation during construction?

____

1-d. Can you point out any factor affecting the adoption of sensing technologies in construction which is related to people or organisation?

____

1-e. Is any aspect of role of the supplier missing from the framework?

____

2. To what extent do you agree that all the factors in the framework are relevant to sensing technology adoption?

- Strongly disagree
- Disagree
- Neither agree nor disagree
- Agree
- Strongly agree

PART 2: Clarity of the framework:

3. To what extent do you agree that the terminology used within the framework reflects the intuition of experts?

- Strongly disagree
- Disagree
- Neither agree nor disagree
- Agree
- Strongly agree

4. To what extent do you agree that every factor within the framework is allocated to a proper stage of sensing technology adoption (proposal, approval and implementation)?

- ○ Strongly disagree
- ○ Disagree
- ○ Neither agree nor disagree
- ○ Agree
- ○ Strongly agree

5. To what extent do you agree that the concepts (factors) and their relations (classification) used within the framework are clear and explicit enough?

- ○ Strongly disagree
- ○ Disagree
- ○ Neither agree nor disagree
- ○ Agree
- ○ Strongly agree

PART 3: Helpfulness and re-usability of the framework:

6. To what extent do you agree that the framework is capable of assisting construction stakeholders and decision makers with a wider adoption of sensing technologies in construction?

- ◯ Strongly disagree
- ◯ Disagree
- ◯ Neither agree nor disagree
- ◯ Agree
- ◯ Strongly agree

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7. To what extent do you agree that the framework is usable and re-usable for the adoption of all types of sensing technologies in construction?

- ◯ Strongly disagree
- ◯ Disagree
- ◯ Neither agree nor disagree
- ◯ Agree
- ◯ Strongly agree

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