NOTTINGHAM TRENT UNIVERSITY

Investigation into the development of a Human Reliability Analysis Framework for the Safety Management of Construction Projects

Umair Khalid
BSc. (Hons), MSc

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Copyright Statement

Declaration

I hereby, declare that this dissertation has not been submitted in part or whole as paperwork for a degree at any other university. I hereby declare that this dissertation is entirely my work and that all parts and thoughts, which have been taken from other persons, are marked and identified by reference.

Signature: ______________________

Date: __________________________

Abstract

Despite the fact that the construction industry is well-known for its enormous economic contribution to the country, the high fatality rate remains a major source of concern for construction professionals. The hazardous, fragmented, cost-driven, and dynamic nature of the industry has been identified as the primary contributor to the construction industry's compromised safety. Despite several initiatives from the government, safety regulatory bodies, and safety professionals to improve safety management, statistics show that occupational safety performance is still unacceptable. In fact, the construction industry is still grappling with identifying the critical factors influencing safety performance. Consequently, contemporary practices are incapable of dealing with the current H&S challenges. To overcome safety issues, it is critical to integrate underlying safety factors affecting safety performance into safety management systems. As a result of the aforementioned issues, the goal of this study was to investigate the underlying factors influencing safety performance in the UK construction industry and propose a framework to address the shortcomings by incorporating advanced immersive technologies for H&S management.

This study took a systematic approach, first identifying the critical factors that have a significant impact on the safety performance of construction projects through a detailed literature review, which served as the foundation for developing an initial framework. These factors were classified into several clusters, which included organisational, managerial, legislative, social, environmental, and personnel considerations. Human/personnel factors were discovered to have a significant impact on occupational health and safety on construction projects, accounting for approximately 80% of construction site accidents; thus, the underlying factors were investigated further in this study. In order to supplement the findings of the literature review, a mixed-method approach was used to scope the working framework for overcoming the H&S challenges influencing safety performance. This involved conducting a

total of 34 questionnaire research which helped to refine the research findings and shaped the proposed framework to assess human error in construction projects. Afterwards, a qualitative approach involving semi-structured interviews was used to validate the proposed framework. In total, 20 experts took part in the interviews, and the results were compared to the initial findings to validate the research findings, as well as the proposed framework, was shown to the participants to validate its working.

The research findings suggested that the leading causes of human error are human personnel traits such as human behaviour, attitude, risk assessment, experience, and hazard assessment. Furthermore, to investigate the occurrence of human error, accident causation models have been studied to analyse the relationship between the latent and proximal human factors. The human reliability analysis (HRA) technique was used to manage human error in construction projects. Several HRA techniques have been examined to determine the best fit framework and the proposed framework was created using the HRA technique, which has been proven to be an effective method in safety-critical industries. Furthermore, immersive technology has been proposed and integrated into the novel framework to develop a viable safety management framework. The proposed immersive safety management framework was validated by respondents.

Dedication

I dedicate this research to my entire family, especially my parents Nighat-un-Nisa and Muhammad Khalid Qureshi for their immense support throughout this research, my siblings and uncle Ejaz Qureshi for all the support they could bring into it, and to my lovely friends who made this journey enjoyable.

Acknowledgements

First and foremost, I would like to express my appreciation and a big thank you to Dr Amrit Sagoo, my director of studies, for his enthusiastic supervision and guidance throughout this research. Your constant input, expertise, constructive criticism, feedback, recommendations, and moral support are greatly appreciated. Apart from this research, you have taught me endurance, courage, patience, hard work, and diligence, all of which have helped me finish the research on time. I'd also like to express my gratitude to my second supervisor, Dr Benachir Medjdoub, for all of his tremendous assistance, guidance, and encouragement throughout the process, particularly his critical but constructive feedback, which aided in the final output of my thesis. I would further like to extend my gratitude to the Department of Construction Management at Nottingham Trent University, where I worked as a part-time lecturer for nearly 3 years.

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1. Introduction

This chapter outlines the research background and explains the principle research aim and objectives underpinned by this research on H&S management in the construction industry. The research rationale has also been addressed in this chapter to identify the importance of the study based on construction industry needs. The brief research methodology has been highlighted for consideration as well as the research process has been presented, and lastly, the structure of the research thesis has been outlined.

1.1. Research Background

The significance of the construction industry cannot be underestimated as it is considered one of the largest industries and most dynamic drivers of the economy that employs millions of people in the country (Rostami *et al.*, 2015). Around 2.4 million people in the UK work in the construction industry which contributes £113 billion to the country's economy equivalent to 6.8% of the country's GDP (Office of National Statistics, 2018). Despite its worth in generating revenue, it is also a well-known fact that the construction industry is one of the most hazardous, labour-intensive, fragmented and dynamic industries (Wang *et al.*, 2019) and is ranked as the second top industry after agriculture with the highest accidents in 2018/2019 in the UK (HSC, 2019). In the United Kingdom, around 22% of total occupational fatalities are from the construction sector, as reported by the Health and Safety Executive (HSE) (HSC, 2019). In 2018/19, 30 workers in the construction industry became the victim of fatal injuries, and 2420 faced non-fatal injuries at the workplace in Great Britain (HSC, 2019).

The uniqueness of construction is its hazardous nature due to a range of construction activities comprised of working in difficult situations and relying intensively on heavy machinery and equipment (Durdyev *et al.*, 2017). Construction workers are exposed to hazardous working conditions such as working at heights and being stuck and caught by construction equipment and machinery on sites which often lead to accidents (Mohammadi *et al.*, 2018). The notorious nature of the construction industry has catastrophic effects on productivity which is traditionally measured in the parameters of cost, quality and time (Hare *et al.,* 2006). Abubakar *et at.,* (2015) stated that among the other performance parameters, H&S is considered one of the key parameters besides the traditional parameters (time, quality and cost) which can easily be compromised by the lack of effective H&S management. Thus, the improvement in occupational health and safety stands inevitable as well as a great concern for the researchers as the accidents come with enormous costs and undermined productivity.

Along with economic loss, this issue also comes with the loss of indispensable human lives, illness, skilled workers and huge compensation costs (Benjaoran and Bhokha, 2010). Furthermore, accident costs could be categorised into direct and indirect costs in the construction industry (Haupt and Pillay, 2016). The direct costs are termed the 'tip of the iceberg' and involve the accident insurance compensation costs and injuries costs. The UK economy lost £1.2 billion in direct costs due to work-related illnesses and accidents in the construction sites which comprises 8% of total costs across all industries (HSE, 2019). Subsequently, Smallwood and Haupt (2007) stated that indirect or submerged costs are 14.2 times direct costs triggered in terms of reduced performance, low productivity, delays and loss of property. This huge loss of construction costs and important human life demands the construction industry for better safety performance.

In the UK construction industry, the H&S issues have for long pinched the construction industry and lead to a lot of studies on the causing factors as well as resolving techniques. Latham (1994) "Constructing the team" and Egan (2002) "rethinking construction" were noteworthy studies on construction industry performance that mentioned H&S as one of the key drivers for improved performance. More recently, in the UK the research trend is towards commitment towards safety, challenges in implementing safety in the construction industry, and the introduction of advanced digital technologies in safety management such as virtual technologies and BIM. For instance, Shepherd et al. (2021) identified the challenges towards the safety of workers from diverse demographics and backgrounds within the UK construction industry. Ganah and John (2017) proposed a BIM-based framework for better H&S practice on-site and highlighted the BIM's potential in managing safety practices and procedures. Similarly, Goulding et al. (2012) developed a prototype using virtual reality technology for improved safety management in the construction industry. A wealth of research has been carried out in the construction industry to identify the factors responsible for poor H&S, however, mainly focused on a specific country or region (Abdul-Rashid *et al.*, 2007; Kadiri *et al.*, 2014; Hamid *et al.*, 2019). Based on the limited evidence of safety factors within the UK context, this research, therefore, aimed to identify safety factors and highlight factors which has the most impact on safety performance.

Consequently, considering the hazardous nature of the construction industry several countries have regulated the safety management system. The United Kingdom's, Health and Safety Commission (HSC) legislated Health and Safety at work etc Act 1974 to propose the occupational health and safety guidelines which were later upgraded to H&S in 2007 called Construction (Design and Management) Regulations 2007 (CDM). Hence, construction safety management is the process of managing safety regulations, practices and procedures before and during the construction phase (Abas *et al.*, 2020). Besides safety regulations, safety management practices also contribute momentously to safety management. The literature reveals that the traditional H&S practice is carried out in two phases, during the first phase called as pre-construction phase, safety is planned and executed and monitored in the construction phase of construction (Zhang *et al.*, 2013a). It is obvious that along with complying with the regulations, there's a need for a robust safety management system within the organisation to plan, do, act and check the safety management (HSE, 2013a). Several types of research have been conducted to propose safety management systems or frameworks for improved safety performance (Gunduz and Laitinen, 2017; Guo, Yu and Skitmore, 2017a; Alkaissy *et al.*, 2020; Nnaji and Karakhan, 2020; Khalid *et al,*. 2021). Similarly, researchers have also highlighted the potential factors and barriers affecting safety management to rectify the issues (Manu *et al.*, 2014; Franciosi *et al.*, 2019; Buniya *et al.*, 2020; Nawaz *et al.*, 2020).

To overcome the issues mentioned above, researchers have developed safety management systems, frameworks, models and rating systems to put resistance to the highlighted H&S issues. Zhou, Goh and Li (2015) stated that construction H&S research revolves around three domains; safety management process, behavioural safety and organisational (safety culture and climate) safety. Bezalel B and Mohamed H (2016) mentioned that existing safety management systems are based on risk management, cultural safety management, and behavioural management prospectives. Although promoting a safety culture, behaviour and risk management helps towards better performance of safety, however, the literature reveals there are many other factors responsible for accidents on construction sites (Abas *et al.*, 2020).

Subsequently, research on accident causal factors has been of significant importance for researchers in the construction industry. For instance, Yu et al. (2014) analysed the factors affecting the safety performance of metro construction in China. Similarly, Ismail, Doostdar and Harun (2012) analysed the safety factors for a specific project in Malaysia and highlighted personal factors as the most influential factor for safety management. Mohammadi, Tavakolan and Khosravi (2018) listed thirteen factors that could influence safety performance from the literature review. Hu et al. (2011) study the factors that affect the risk of falls on construction sites. moreover, Furthermore, Naiduwa-handi and Silva (2017) studied the factors influencing workers' behaviour towards safety on construction sites. Othman et al. (2020) penned on finding the factors that route the success of a safety management system. Hence, several researchers have penned on causal factors of safety performance, however, these studies are based on a specific realm i.e. location, project type or personnel feature. Moreover, these studies do not present a method or system to measure or manage the safety factors.

Against the given above background, more recent trends in the construction industry have been towards the introduction of advanced digital technologies. Construction safety management systems circle around two notions which are either management-driver or technology drivers (Zhou, Goh and Li, 2015). Numerous digital tools have been introduced by safety professionals for safety improvement in the fields of automation, tracking and visualization (Teizer *et al.*, 2013a). Li et al. (2018) critically analysed the visualization technologies used in the construction industry and found that technologies like virtual reality or augmented reality are helpful for hazard identification and training workers. Other prominent technologies that have been introduced in the construction industry found in the literature are; GPS and GIS for location tracking, 4D simulations for hazard identification, application of unmanned aerial systems (UAS) for inspection, BIM-based hazard identification (Hongling et al., 2016; Guo, Yu and Skitmore, 2017a; Melo et al., 2017a; Alizadehsalehi et al., 2018). It is obvious from the literature that in safety management, technology has applications for risk assessment, hazard identification and training purposes (Guo *et al.*, 2018).

1.2. Research rationale

The rationale of this research is based on the fact that the UK construction industry still constitutes a bad reputation and represents maligned H&S performance. Government interventions, regulations, guidelines, technological advancement, and safety professionals' contributions have helped the construction industry to H&S to a certain extent, however, it is evident that the construction industry needs a more inclusive approach to overcome the shortcoming. Specifically, the reliance on conventional safety management systems only on a few safety factors, misalignment of the safety factors study from safety management systems, and lack of integration of safety management systems and lack of digital technology in safety management are the key issues affecting safety management in the construction industry. Therefore, given the fatalities encountered each year, it is inevitable to review accident causation factors and figure out the key factors causing many accidents on construction sites. Moreover, along with figuring out the causes, there's a need to rethink the safety management methods used in the construction industry and develop a novel approach to safety management.

1.3. Research Questions

Based on the above discussion, the following research questions have been established.

Q1. What are the key factors affecting safety management in the construction industry in the United Kingdom?

Q2. What methods/systems are used in the construction industry to eliminate key factors influencing safety management?

Q3. What are the shortcomings of contemporary safety management systems in the construction industry?

Q4. How safety management can be improved in the construction industry by incorporating advanced digital technologies.

1.4. Research Aim & Objectives

This research aims to develop a novel framework to eliminate the accident causal factors from safety management allowing construction professionals to improve safety performance in the UK construction industry. Given below are the research objectives derived to achieve the research aim;

1. Determine the current H&S performance, practices, and improvement efforts in the UK construction industry.
2. Undertake a critical review of safety causal factors in H&S management and determine the key factor that contributes to accident causation and develop an initial framework.

3. Explore the impact of those factors and remedial methods/techniques as well as the advanced digital technologies to overcome the issue.
4. Conduct quantitative research to get the construction H&S professional input aimed to develop a solution for safety management.
5. Develop a framework aiming to eliminate those factors from the construction process utilizing advanced digital technologies.
6. Validate the framework and evaluate the appropriateness of the framework by employing a qualitative research approach and concluding the research.

1.5. Research Methodology

A research methodology is a specific technique or method to acquire pertinent knowledge about a topic or a problem (Fernandez, 2020). The choice of which research method to use depends on the nature of the research problem (Noor, 2008). Saunders et al. (2013) argued that the research methods can also be comprehended from the research philosophy followed by the research approach and suitable strategies in pursuit of research objectives. Therefore, it is important to identify the research philosophy, research approach and strategies for the given methodological choices. To acquire a better understanding of research methodologies, some philosophical terms are frequently used over the past few years such as research ontology, epistemology, positivism and interpretivism (Dainty, 2008). The research philosophy describes how knowledge is developed and what is the nature of knowledge (Saunders et al., 2009). The term epistemology deals with the method of getting knowledge & understanding within the research domain (Saunders et al., 2009). Hence from the philosophical perspective, the research entails a pragmatic approach to acquiring about the research domain. This research approach was adopted based on the ontological and epistemological positions of the research. This research entails a subjective/idealistic ontological position and a social-constructive epistemological position. The Epistemology of pragmatic philosophy drives the research hypotheses from natural observations and law-like generalizations (Saunders et al., 2009). Pragmatism is another philosophical school of thought also known as the "Philosophy of Common Sense". The scientific philosophy of pragmatism believes that conceptions are only helpful when they support actions (Kelemen and Rumens, 2008).

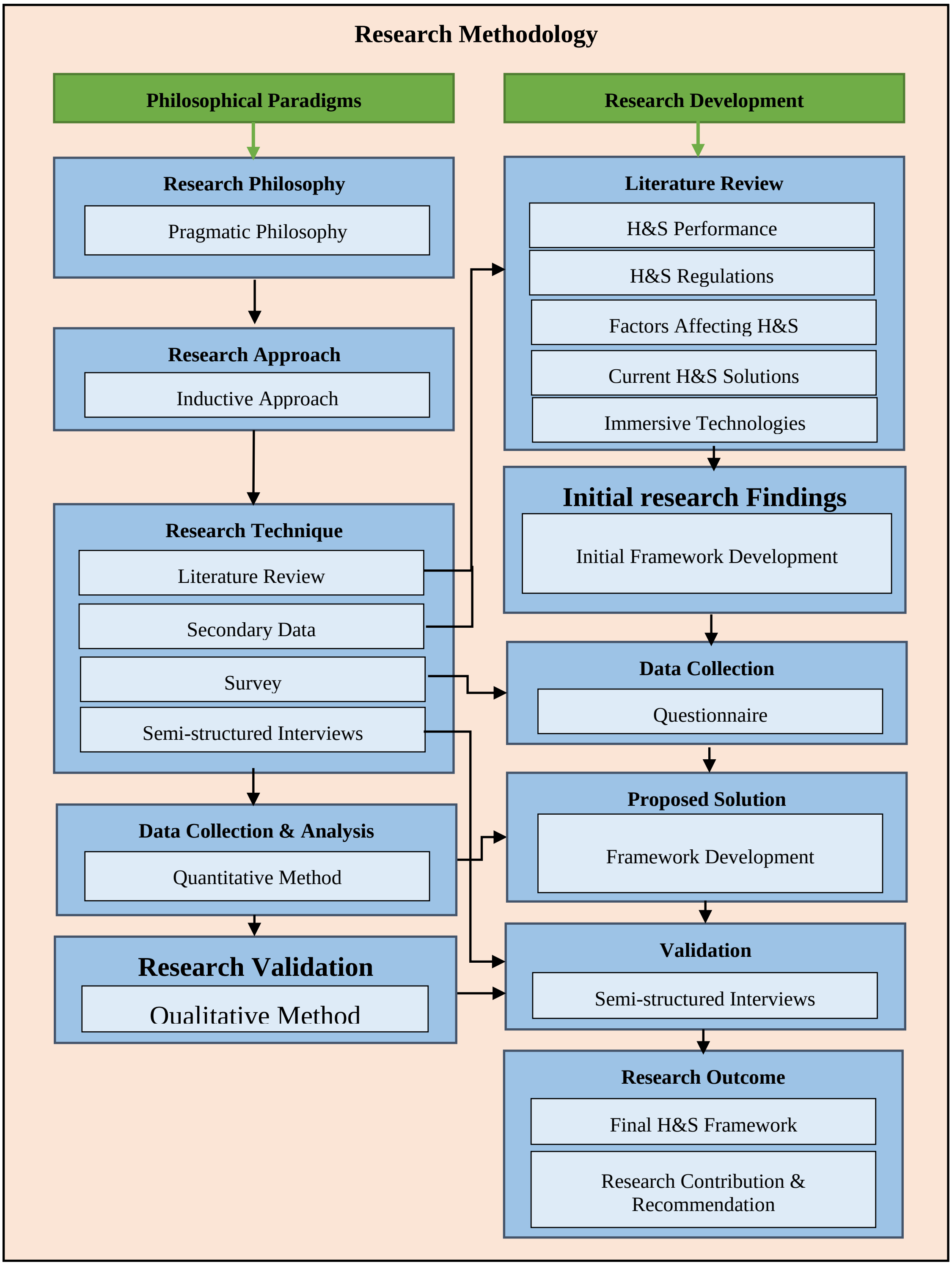

Figure 1.1: Research Methodology

Subsequently, this research follows a mixed-method approach to develop a framework for essential H&S improvement. The mixed-method approach has been used frequently to define problems and identify solutions to improve as well as enhance human knowledge with the creation of innovative frameworks (vom Brocke, Hevner and Maedche, 2020). Therefore this approach has been selected to identify the safety management problem and develop a novel framework to improve safety performance. Furthermore, regarding the research strategy, Knight and Ruddock (2009) suggested multiple research strategies to achieve research objectives. Hence, a literature review, semi-structured research survey and semi-structured interviews have been selected as the appropriate strategies for the research. The detailed research methodology including the philosophy has been shown in Figure 1.1 above.

1.6. Research Process

The research has been carried out in four essential stages. The first stage entailed investigating the research challenges, as well as gaining a better knowledge of the research topic and examining current corrective techniques. Following that, the second step builds a research instrument based on the first phase's findings and conducts data collection. The third phase entails data analysis and framework building based on the study findings, and the final research objective of validating the framework is accomplished through semi-structured interviews in this phase. These four stages of this research have been described briefly below.

Stage 1: Literature Review

The key aspect of this research has been the literature review. It allowed this research to examine and comprehend existing knowledge about H&S methods, flaws, and factors affecting safety in the construction business and contributed to the initial framework development. Furthermore, it laid the groundwork for this research by identifying research gaps and assisting in the compilation of research questions. Moreover, rigorous literature examined the technological interventions in the various industries and identified appropriate technologies suitable for safety framework development. Chapters 2 & 3 critically analyse the factors affecting H&S, prevailing safety practices, and potential strategies to mitigate the factors.

Stage 2: Questionnaire Survey

One of the most crucial strategies employed in this study to improve research knowledge was the questionnaire survey. In a quantitative study, questionnaire surveys are commonly used to collect data from certain groups of people to produce knowledge and theories. The purpose of the questionnaire in this study was to gain an understanding of the research questions as well as to investigate their knowledge of accident causation, factors affecting H&S, human reliability analysis (HRA), and their feedback on the use of immersive technology to eliminate causal factors. To gather participants' perspectives on the reasons for the accident and human reliability evaluation, an online questionnaire for health and safety professionals (safety Leaders, Directors and Top safety managers) was developed in three sections.

Stage 3: Framework Development

The proposed framework was created using the findings of a comprehensive literature analysis that lead to the development of an initial SMS framework and through a semi-structured questionnaire survey aimed at construction safety professionals. The proposed framework development process involved identifying the potential causes of construction accidents, evaluating the weaknesses of existing safety measures in the construction sector, and reviewing viable solutions to solve the shortcomings. A detailed commentary on the proposed framework development has been carried out in Chapter 5.

Stage 4: Research Validation

After the framework was developed successfully, the study's next goal was to evaluate the research findings. This was accomplished through semi-structured interviews with construction sector safety specialists. Twenty interviews were conducted with the safety and behavioural experts from within the construction industry and their feedback has been embedded into the research findings. The qualitative research validated the proposed H&S framework and yielded some noteworthy results on H&S management in the construction industry, with some implications. The method for analysing semi-structured interviews has been discovered as Interpretative Phenomenological Analysis (IPA). The development of the provided framework has been validated by validating each study objective. A detailed discussion on research validation is provided in Chapter 6.

1.7. Contribution to knowledge

This research contributed significantly to the development of the immersive safety management framework. The research contribution emerged after the identification of critical safety factors and the gaps in the prevailing safety methods to manage the identified factors. Thus this research has contributed to fulfilling the identified gap in professional practice as well as in knowledge. The research finding would be a massive milestone toward safety planning in the construction industry. The research will not only provide construction professionals with a tool to manage safety but it will also provide guidelines to future researchers to contribute to the same domain.

1.8. Thesis Structure

The thesis consists of seven chapters which are briefly described below. Figure 1.2 below graphically presents the structure of the thesis.

Chapter One: Introduction to Research

This chapter discussed the background, and the research rationale, and presented the research problems, as well as the study context. The research aim, objectives, and research questions have also been illustrated in this chapter. The study's reasoning and justification are also presented. It also includes a summary of the work completed, the contribution to knowledge, and the thesis format.

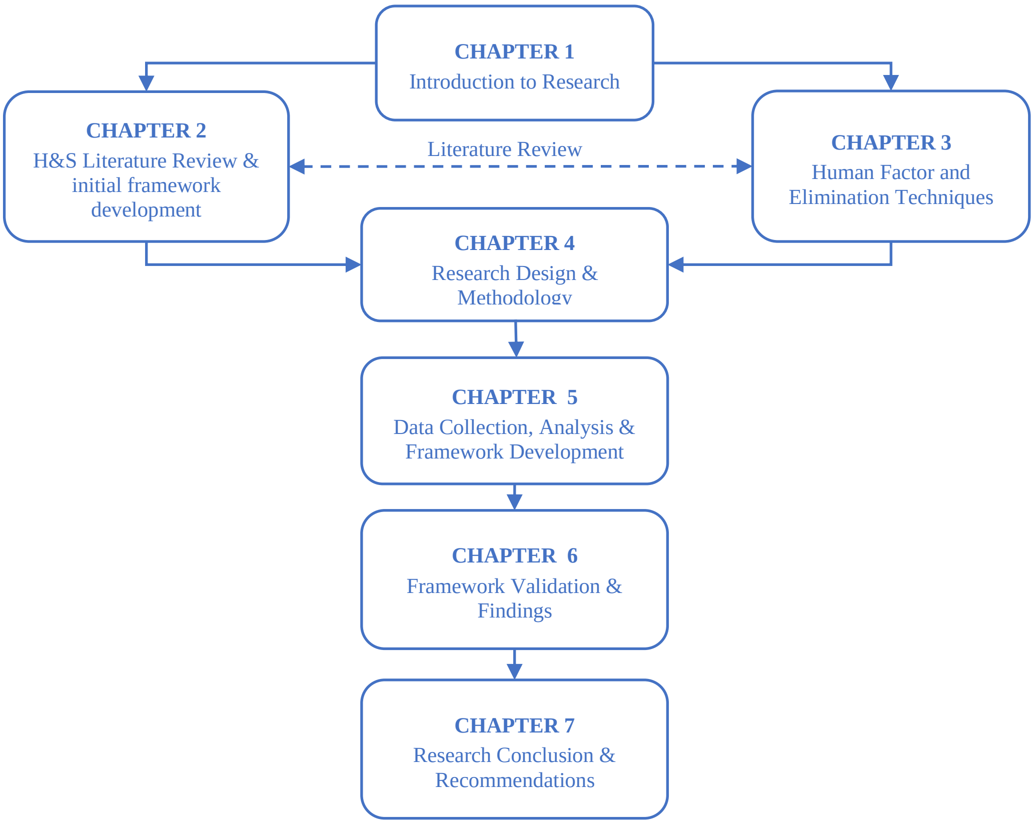

Figure 1.2: Thesis Structure

Chapter Two: H&S Literature Review & Initial Framework Development

Chapter 2 highlights the H&S statistics of the construction industry which have a significant impact on the overall performance of the industry. It then reviews the prevailing safety practices through an extensive literature review (section 2.4). Afterwards, an extensive analysis of the factors affecting the safety performance of the construction industry has been carried out using empirical research methods specifically designed for the comprehensive review. Around sixty critical factors have been highlighted and an initial framework was proposed to manage those factors.

Chapter Three: Human Factor and Elimination Techniques

After identifying the pertinent safety factors in Chapter 2. This chapter aimed at exploring the prominent factors having a momentous impact on safety performance. Through a rigorous literature review based on accident investigation within the UK construction industry, the research has recognized human factors causing most of the accidents. Then, an in-depth literature review was conducted to reveal the methods and techniques used to overcome human factors in safety-critical industries as well as the construction industry. Moreover, this chapter identified the path to developing a robust framework to minimise the impact of the highlighted factors.

Chapter Four: Research Design & Methodology

This chapter presented the research methodology, philosophical standing and research paradigm associated with this research. The chapter also examines a variety of research methods, as well as adopted an appropriate research methodology to achieve the research objectives. This chapter also justified the study methods and design employed.

Chapter Five: Data Collection, Analysis & Framework Development

A comprehensive discussion on data collection and analysis has been made in this chapter. First of all, data collection strategies persisting data sampling, research instrument development, distribution and collection have been presented. Followed by an in-depth discussion on the quantitative analysis of collected data. Afterwards, a safety management framework has been proposed based on the research findings.

Chapter Six: Framework Validation & Findings

Through in-depth interviews with H&S professionals in the construction industry, this chapter validates the study findings from the preceding chapter. A detailed discussion on the participants, interview strategy and the finding has been carried out to further investigate the research questions as well as validate the research findings to improve the H&S performance of the UK construction industry.

Chapter Seven: Research Conclusion & Recommendations

The study's key conclusions and recommendations were presented in Chapter 8. It highlights the findings of the research questions, as well as the original contribution to knowledge, as well as the study's limits and recommendations for future research.

1.9. Chapter Summary

The first chapter presented a high-level overview of the research motivation, adopted methodology, research process and knowledge contribution. Moreover, it illustrated the structure of the thesis for the reviewer and discussed each of the achieved objectives. This next chapter examined the literature review on factors affecting health and safety followed by several chapters.

Chapter 2: H&S Literature Review & Initial Framework Development

2. Introduction

This chapter reviews the H&S performance of the construction industry as well as critically reviews the factors affecting health and safety performance using empirical research methods designed for the comprehensive review. Firstly, the performance of the construction industry from the H&S perspective has been examined through the literature and regulatory bodies' reports followed by the significance of the construction industry in the economic growth of the United Kingdom. Later, to review the factors causing fatalities and accidents on construction sites, an empirical research technique has been designed to review the past 15 years of literature on accident causal factors.

2.1. Overview of H&S Performance in the Construction Industry

The debate on the construction industry's performance has a historical existence and can be traced back to the 1930s. Both government and private sectors initiated several improvement strategies to enhance industry performance. Sir Alfred Bossom in his report "Building the skies" in 1934 highlighted adversarial behaviour as one of the factors behind the poor performance of the construction industry (Alfred Bossom, 1934). Similarly, Simon Report (1944) and Benwell (1967) criticized the construction procurement methods, construction contracts, and team relationships and suggested the improvement of the construction industry (Hillebrandt, 2008). Latham (1994) in his report "Constructing the team" described the construction industry as 'fragmented', 'adversarial', 'ineffective', and 'incapable of delivering to the customers. He further stated that the client should be at the core to make an integrated team for more collaborative and effective working and risk allocation should be carried out for a safe working environment. Similarly, Egan (2002) also advocated for better leadership, integrated working, legislation, and safety management in construction projects, and called for dramatic improvements in the industry. All the issues highlighted by these studies have a direct effect on safety management which has been a serious concern for safety professionals for the past few decades.

Subsequently, occupational health and safety (H&S) is considered a global challenge for the sustainability and development of society and the economy. The construction sector is one of the riskiest, most dynamic and most challenging industries (Wang *et al.*, 2019; Fonseca, 2021) and has been continuously ranked among the top three industries with the highest accidents rate over the past decade based on the statistics provided by H&S authorities in different counties (Ahmadian *et al*., 2018). H&S has been regulated by almost every country around the globe but it is still a concern for practitioners and researchers internationally because of the high rate of accidents. According to the International Labour Office (ILO), more than 2.3 million people die each year due to work-related fatal injuries. Furthermore, around 374 million people suffer non-fatal injuries each year resulting in a loss of 4% of the Gross Domestic Product (International Labour Organisation, 2021). Hence, this loss comes with a considerable social and economic cost to the individuals as well as to the businesses involved.

In the United States, according to the Bureau of Labour Statistics, a total of 5,147 fatal workplace injuries were recorded in 2017 with a rate of 3.5 per 100,000 full-time workers (Bureau of Labor Statistics US Department of Labor, 2018). Figure 2.1 below shows the number of fatal work injuries from 2003 to 2017 provided by the Bureau of Labour Statistics. Out of 5,147 fatalities in 2017, 971 (20.7% of the total) were from the construction industry, that is, one in every five workers becomes the victim of fatal injury, which makes the construction industry top third most dangerous industry (Bureau of Labor Statistics US Department of Labor, 2018).

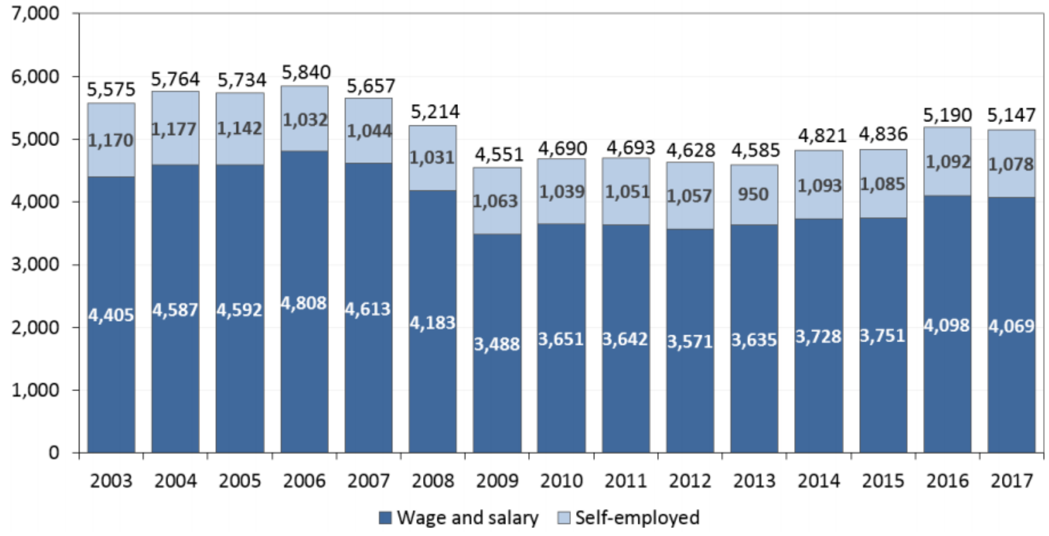

Figure 2.1: Number of fatal work injuries by employee status, 2003-17 (BLS, 2018)

Among the other incidents, in 2017 falls, slips and trips caused more fatal work injuries over the past 26 years as reported by the Census of Fatal Occupational Injuries (CFOI) and inclined to 887 (17% of total) worker death. Figure 2.2 shows the fatal causalities caused by different types of incidents(Bureau of Labor Statistics US Department of Labor, 2018).

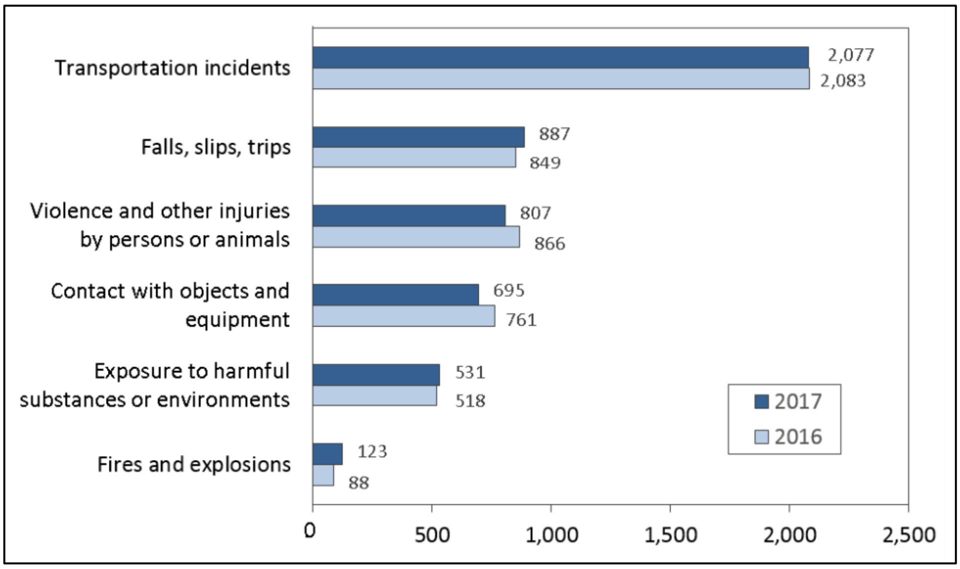

Figure 2.2: Number of fatal work injuries by major incidents, 2016-17 (BLS, 2018)

Besides fatal work injuries, statistics also show 2.8 million non-fatal workplace injuries and illnesses reported in 2017 by private industry employers which account for 2.8 cases per 100 workers in the United States. Bureau of Labour Statistics reported that the number of non-fatal workplace injuries and illnesses reported in 2017 is 45,800 fewer as compared to last year (BLS, 2018). According to the Survey of Occupational Injuries and Illnesses (SOII) a USA federal cooperative program that publishes statistics on non-fatal occupational injuries and illnesses every year, the number of non-fatal injuries and illnesses is declining each (BLS, 2018). Figure 2.3 below shows the rate of workplace injuries per 100 full-time workers from 2003 to 2017 categorised by different case types.

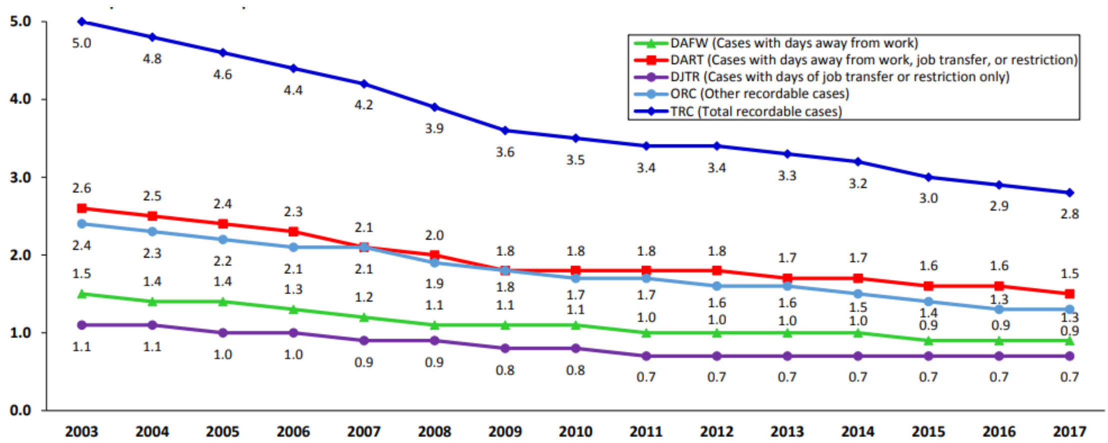

Figure 2.3: Non-fatal Occupational injuries rates by case type, 2003-17 (BLS, 2018)

2.2. H&S Performance of United Kingdom

Occupational health and safety is of significant importance for the construction industry throughout the world. Construction being one of the prominent industries in making significant revenue to the country's Gross Domestic Product (GDP) and hosting 10% of the workforce also shares substantial responsibility for workplace safety (Department for Business Information & Skills, 2013; HSE, 2020). Regardless of the comprehensive efforts by the safety professionals and governmental H&S organisations in implementing safety regulations, statistics still reflect high workplace fatal and nonfatal injuries. When compared to the other countries, UK workplace H&S performance reflects the best statistics across Europe. The UK consistently shows the lowest standardised fatal injury rates across Europe for years, lesser than other large economies in Europe. In 2016, UK standardised fatal injury rate was 0.53 per

100,000 full-time workers which revealed one of the lowest across Europe. Moreover, UK's average three-year (2013-2015) fatal injuries rate was recorded as 0.52 per 100,000 workers stood the lowest across Europe. Figure 2.4 below shows the standardised incidence rate of fatal injuries at the workplace per 100,000 employees for the year 2016 (Health and Safety Executive, 2018).

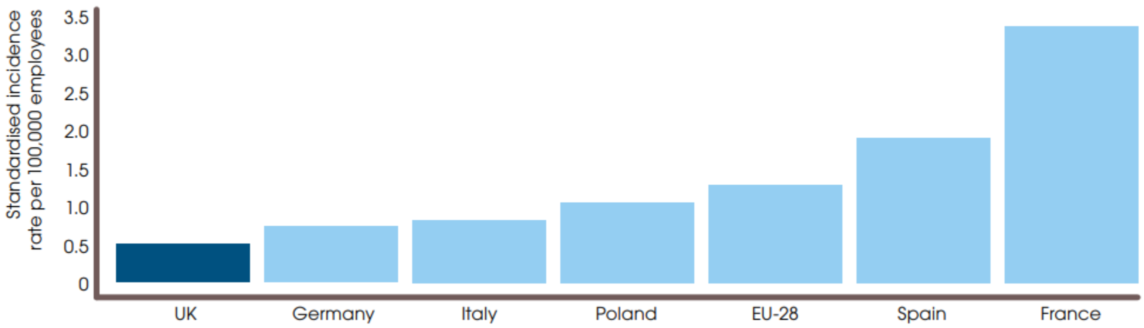

Figure 2.4: Standardised Incidence rate Europe 2016 (HSE, 2018)

In 2020/21, a total of 142 workers became the victim of fatal injuries at the workplace in Great Britain (HSE, 2020). There has been an increase seen in the reported fatalities in the past couple of years, however, in numerical terms, the number of incidences remained level in recent years with the average annual number of 142 workers killed at the work over the past five years. Figure 2.5 shows the number of fatalities since 2010/11 according to HSC statistics.

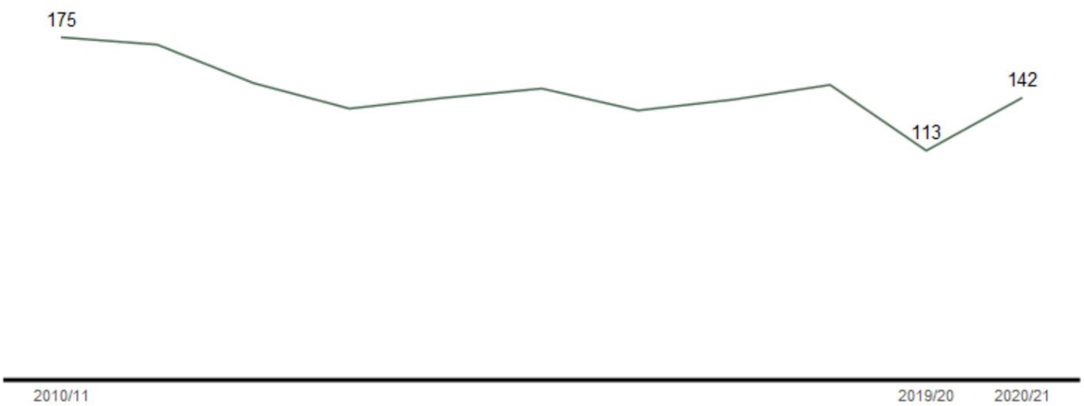

Figure 2.5: HSC statistics for the past 10 years (HSE, 2020)

The rate of fatal injuries per 100,000 workers has been showing a downward trend over the past few decades and in the last few years, it is quite consistent with the annual average of around 140 fatalities per 100,000 workers from 2016/17 to 2020/21(HSE, 2020). However, compared with 253 twenty years ago in 1998/99 the number of fatalities has decreased due to the legislation imposed by the government (HSC, 2019). Figure 2.6 & Figure 2.7 below show the number of fatalities per 100,000 workers and the fatalities rate since 1981 (HSC, 2019).

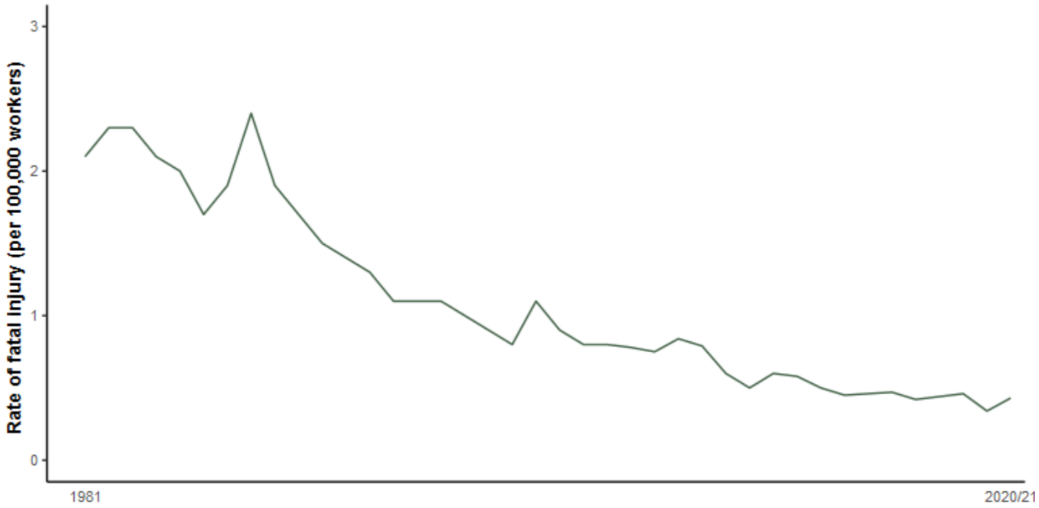

Figure 2.6: Fatalities rate per 100,000 workers since 1981 (HSC, 2019)

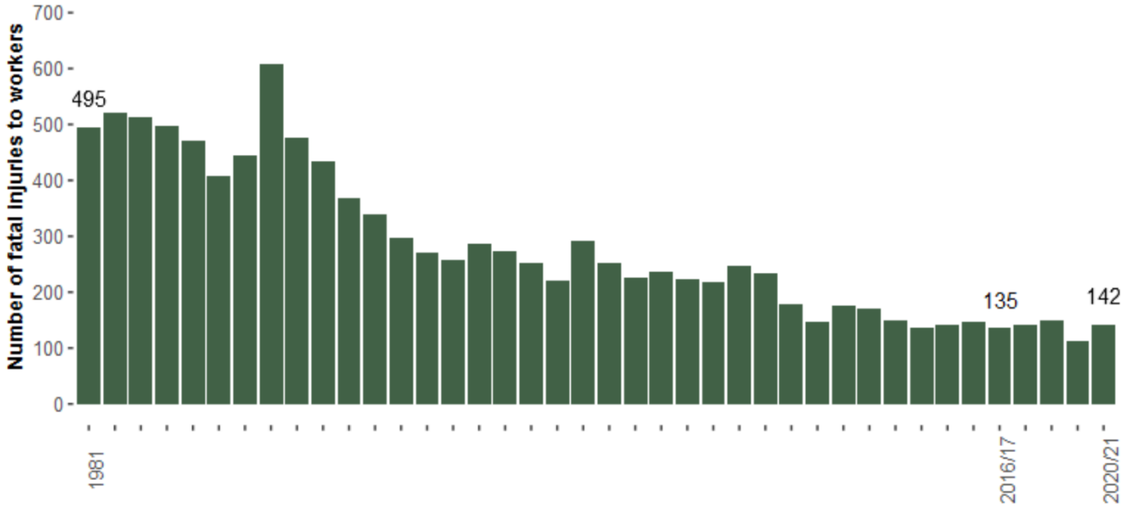

Figure 2.7: Fatalities per 100,000 workers since 1981 (HSC, 2019)

The overall UK's H&S performance is quite satisfying however, compared to other industries construction is one of the top industries responsible for occupational accidents and fatalities.

The number of incidents in 2020/21 for almost every industry is broadly lined up with the annual average incidents over the past five years, however, the number can fluctuate from year to year. Figure 2.8 below shows the fatal injuries by the industry for the year 2020/21 and the annual average per 100,000 workers for 2016/17 – 2020/21 (HSE, 2020).

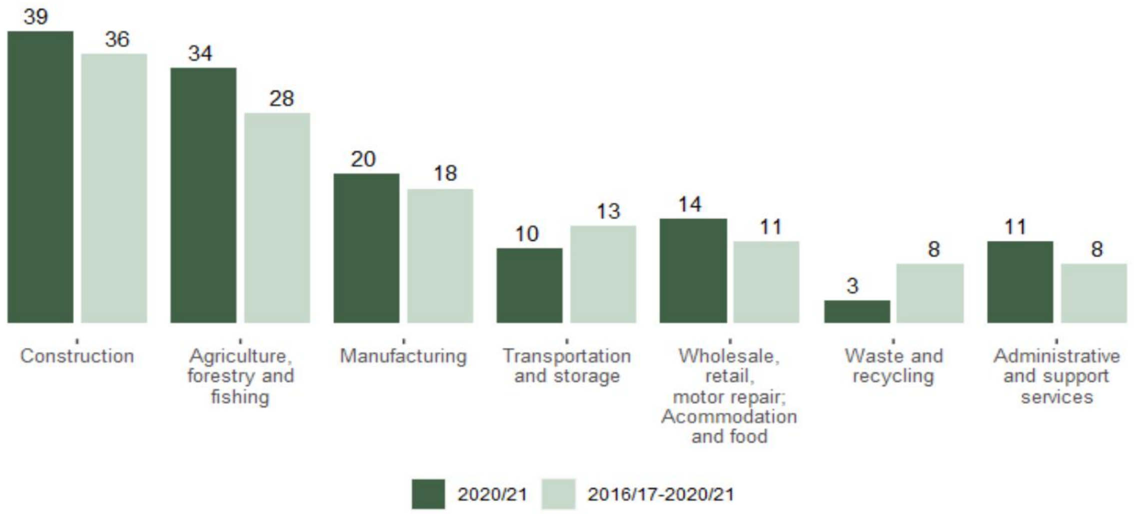

Figure 2.8: Number of fatalities by industries (HSE, 2020)

In the construction sector, an increase has been seen in the number of fatal injuries since last year with total fatal injuries of 39. However, the number of fatalities in the construction industry still contributes a significant number to the total number of occupational fatalities. In 2020/21, the construction industry’s contribution to occupational accidents has been counted as 27.4% and listed as the top first industry responsible for occupational accidents (HSE, 2020). This makes the construction industry the top contributor to the loss of precious life as well as enormous compensation amounts. Figure 2.9 below shows the number of fatalities in different industries for the year 2020/21.

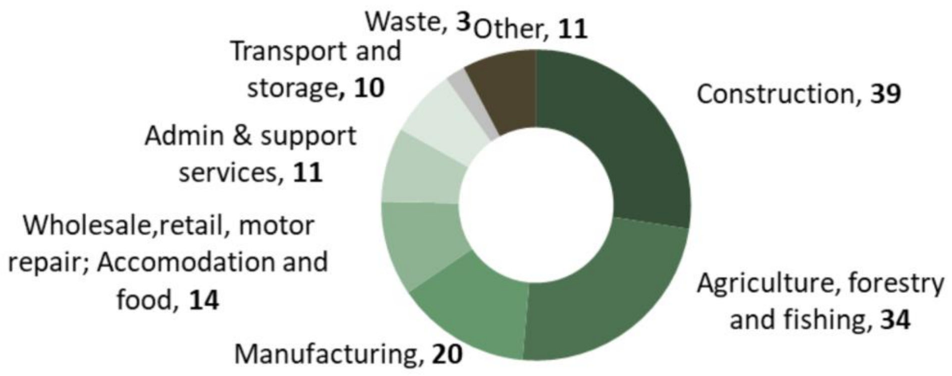

Figure 2.9: Fatal Injuries by main industry type - 2020/21 (HSE, 2020)

To further investigate the causes of accidents, around three-quarters of the total fatal injuries in the past five (2016/17 – 2020/21) years can be categorised into five different accident kinds. Falling from a height has been the most common kind of accident in the past five years and caused an average of 36 fatal injuries each year. Struck by a moving vehicle has been the second main cause of an accident followed by being struck by a moving object, trapped by something and contracting with moving machinery (HSC, 2019). Figure 2.10 below shows the number of fatal injuries to workers by accident types in 2018/19 and the annual average for 2014/15 – 2018/19.

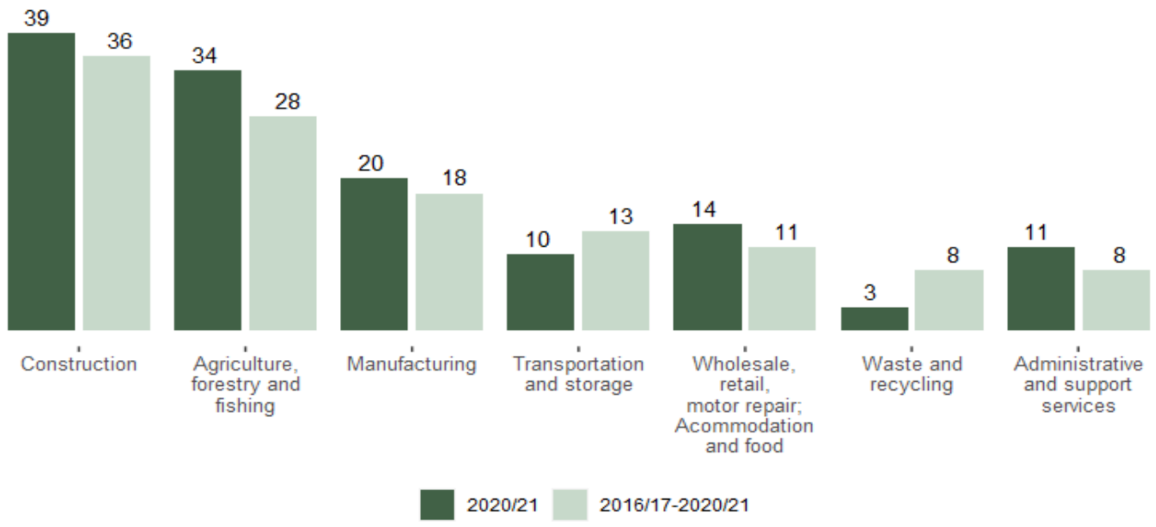

Figure 2.10: Number of fatal injuries 2016/17 - 2020/21 (HSC, 2019)

2.3. Significance of the UK construction Industry

The significance of the UK construction industry cannot be undermined considering its contribution to the economy. Besides its notorious nature, it is also considered one of the main economic drivers of the country's economic growth and provides opportunities and jobs to millions of people (Yi and Li, 2018). The UK government's briefing paper stated that the construction industry contributed 118.9 GBP billion to the economy in 2019 which counts for 7% of GDP (Office for National Statistics, 2019). The economic output of the construction industry has grown in the past few years, especially since 2013 from 91GBP to 118GBP in 2019. Figure 2.11 below shows the performance of the UK construction industry over the past decade with a positive trend since 2009 (Office for National Statistics, 2019).

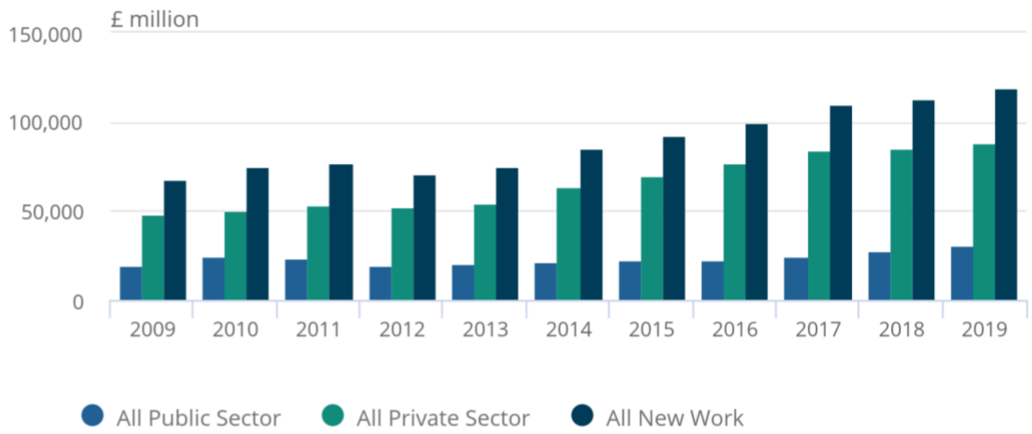

Figure 2.11: Economic outcome of the UK construction industry (ONS, 2019)

Moreover, the UK construction industry also has a major share in employing millions of jobs each year. Office for National Statistics (2019) states that 2.4 million people in the UK have been employed by the construction industry which counts for 6.8% of the total jobs in the economy. Table 2.1 below shows the trend of workforce provided by the constriction industry (Office of National Statistics, 2018). These statistics show that the sustained growth of the industry is essential for the socioeconomic growth of the country. However, the sustainable growth of the industry demands the improved safety of the millions of people working on construction projects.

Table 2.1: Employment in the Construction industry, UK (ONS, 2018)

Year	Millions	% of all Jobs
2010	2.08	6.6%
2011	2.09	6.6%
2012	2.07	6.4%
2013	2.07	6.4%
2014	2.14	6.4%
2015	2.18	6.4%
2016	2.21	6.4%
2017	2.35	6.7%
2018	2.38	6.8%

2.4. Health and Safety Practices in the UK Construction Industry

2.4.1. Health and Safety Regulations

UK Health and safety regulations are enforced by the Health and Safety Commission (HSC) established under Health and Safety at work etc Act. 1974 by making adequate arrangements to propose the health and safety regulations and approve the code of practice (HSE, 2013). Health and Safety Executive (HSE) was then established under HSC to enforce health and safety laws. Health and safety at work etc Act. 1974 implies duties on all the stakeholders to ensure the safety of their workers including members of the public during the project (HSE, 2013). Other subsidiary regulations like The Construction (Health, Safety, Welfare) Regulations (HMSO, 1996) and The Management of Health and Safety at work (HMSO, 1999) have imposed more specific duties on contractors for risk assessment and health and safety planning.

The principal set of regulations for construction was introduced in 2007 called Construction (Design and Management) Regulations 2007 followed by an updated version in 2015. CDM regulations imply roles and responsibilities for all who can contribute to the health and safety of construction projects (HSE, 2007). Detailed requirements for those involved in pre-construction and planning phases are explicitly mentioned in CDM Regulations. Specifically, the introduction of the new role of the Planning Supervisor at the designing phase to follow health and safety exclusively during the design process and documentation such as the Health and Safety File for contractors has led to the formation of new health and safety processes. Therefore, CDM regulations appoint duty on both the principal designer for health and safety planning at the pre-construction phase and on the principal contractor to imply safety arrangements during the construction phase of the project (HSE, 2007).

Moreover, the purpose of CDM regulations is to bring together all the stakeholders involved in the design and construction process to overcome the health and safety issues which arise at different stages of development (Zhou, Whyte and Sacks, 2012). Subsequently, it has also stated that the CDM regulations aimed to bring safety and cultural change in the construction industry by pursuing the philosophy of collaborative working by establishing a team with competence and resources to mitigate the safety risks from the design and construction phases (Baxendale et al. 2000). It also highlights the importance of awareness level of distinctive responsibilities among the stakeholders as well as underpins the collaboration for safe construction during various states of development (P. Perry, 2003). Furthermore, over the years HSC has published a number of guidelines to support construction companies in improving their safety performance by embedding safety measures into the organisational policies. Table 2.2 below shows a few of the prominent guidelines published by HSC in the last 20 years.

Table 2.2: HSC Guidelines on safety management

Guideline	Year	Title
HSG65	2013	Managing for Health & Safety
HSG245	2004	Investigating accidents and incidents
HSG150	2006	Health & Safety in Construction
HSG48	1999	Reducing error and influencing behaviour
RR679	2009	Review of Human reliability assessment methods
RR834	2011	Preventing catastrophic events in construction

These guidelines do not have any statutory or binding other bindings towards safety management. However, they can help construction organisations to strengthen safety management by introducing barriers at different managerial levels for any safety breaches. Moreover, these can be helpful for the leadership to develop safety management systems in the organisations which are essential for vigorous safety management throughout the project lifecycle. For instance, “HSG150-Health and Safety in Construction” advises on essential safety measures to be considered at different project stages. Similarly, “HSG65-Managing for Health and Safety” advocates and guides the development of an integrated safety management system within the organisation for essential safety management. Moreover, these guidelines are helpful for accident prevention, error management, risk assessment and worker training.

2.4.2. Safety Management System (SMS)

The study of the system for management of the safety or Safety Management System (SMS) constitutes the study of three separate terms “System”, “Management” and “Safety”. Therefore, a SMS deals with the safety management of a system under consideration. An SMS is a proactive and systematic approach to managing health and safety in a system. Health and Safety Executive (HSE) defined SMS as “a formal management system/framework or method to deal with health and safety issues” in its published document HSG65-Managing for health and safety (Health and Safety Executive, 2013). Safety management systems (SMS) aim to evaluate the safety policies, procedures and practices to improve safety performance by preventing incidents and accidents (Guo, Yiu and González, 2015). Rasmussen (1997) pioneered the concept of a systemic approach to deal with inevitable accidents rather than eliminating the root causes and latent failures. He further argued for top-bottom systematic safety management incorporating the government and the regulatory bodies above the organisational level. In his model Rasmussen (1997) presented a Risk Management Framework

(RFM) to elaborate on the risk associated at each organisational level (i.e. government, regulator, organisation, management, staff and work) shown in Figure 2.12.

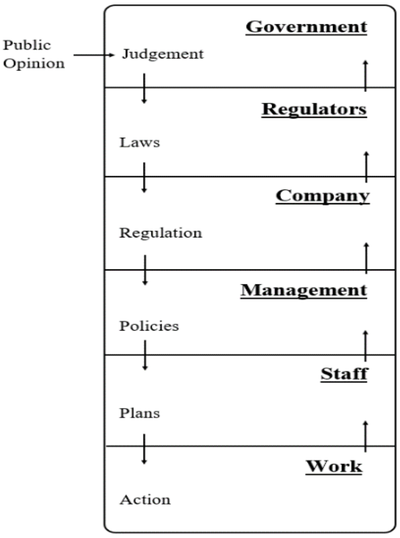

Figure 2.12: Risk Management In The Socio-Technical System (Rasmussen, 1997)

A well-designed SMS can contribute immensely to the successful execution of safety management in the workplace, hence, accommodating the successful completion of the project. Health and Safety Executive (2013) further stated that a safety management system must comply Plan, Do, Check, Act framework to identify the key safety risks involved and highlight necessary actions required in each step of the framework. Therefore, safety management systems need to deal with planning, implementing, evaluating and reviewing safety measures. The key actions required at each step are shown in Figure 2.13 below (Health and Safety Executive, 2013).

Figure 2.13: Plan, Do, Check, Act Framework (Health and Safety Executive, 2013)

In the pursuit of effective safety management, many safety management systems have been proposed by safety professionals in different countries and industries. Gunduz and Laitinen (2017) highlighted 10-steps essential for the development of a safety management framework addressing the factors involved in the safety management for small to medium-sized companies. Similarly, many others have also put the effort to develop safety management systems and frameworks from different perspectives, for instance, management-driven SMS and technology-driven SMS are the two prominent directions of safety management research in the construction industry (Zhou, Goh and Li, 2015). To explore further SMS in the construction industry, an exhaustive literature review has been carried out focusing on the development of SMS and classified into two groups; management-driven SMS and technological-driven SMS.

2.4.3. Management Driven Safety Management Systems (SMS)

As aforementioned, an SMS aims to evaluate safety planning, procedures and safety practices within the organisation for safety improvement. Management driver safety management systems assume that safety procedures and practices help towards safety management (Bezalel B and Mohamed H, 2016). These SMS further presumes that safety procedures and practices act as barriers at different levels of organisational hierarchy to prevent safety breaches and eventually accidents on the construction sites. Additionally, management-driven safety management systems are based on eliminating accident causal factors, indicators, safety risks and worker behaviour management by introducing safety practices and procedures. For instance, Hallowell et al. (2013) developed a system for proactive safety management by monitoring and responding to safety indicators. De Silva and Wimalaratne (2012) introduced a framework for accident prevention in Srilanka’s construction industry by controlling the accident causal factors. Subsequently, Guo, Yiu and González (2015) proposed a safety management model to evaluate the worker's behavioural towards safety for the betterment of safety performance. Table 2.3 below shows some of the management-driven safety systems proposed by different researchers.

Table 2.3: Management-Driven safety management systems

Author	Research Title
(Maiti and Choi, 2021)	An evidence-based approach to health and safety management in megaprojects.
(Wu *et al.*, 2013)	An integrated information management model for proactive prevention of stuck-by-falling-object accidents on construction sites.
(Husin, Adnan and Jusoff, 2009)	Management of safety for quality construction
(De Silva and Wimalaratne, 2012)	OSH management framework for workers at construction sites in Sri Lanka
(Zeng, Tam and Tam, 2008)	Towards occupational health and safety systems in the construction industry of China
(Li *et al.*, 2015)	Proactive behaviour-based safety management for construction safety improvement

2.4.4. Technology Driven Safety Management Systems (SMS)

Considering the role and significance of the construction industry in the economy, researchers and practitioners have been endorsing the use of technology in the construction industry. Especially, the introduction of building information modelling (BIM), and advancements in drawing, management and planning tools have helped the construction industry to fulfil its obligations. However, the construction industry has yet less benefited from technology as compared to other industries, particularly in safety management. Nevertheless, there has been an encouraging trend toward the use of advanced technologies for safety management (Irizarry, Gheisari and Walker, 2012a; Balgheeth, 2016; Frank Moore and Gheisari, 2019a; Fonseca, 2021). More emphasis has been given to technology-driven safety management systems than management-driven systems in the past 10 years by the introduction of state-of-the-art technologies in safety management.

A technology-driven SMS presumes that the application of robust technology can be used to improve health and safety performance. Most technology-driven safety management systems revolve around visualization technology implementation for enhanced communication, planning, risk assessment, and training in an attempt to improve overall safety management (Eiris, Gheisari and Esmaeili, 2018). Moreover, other technologies have also attracted the attention of safety experts for safety monitoring and safety evaluation (Melo *et al.*, 2017a). The introduction of building information modelling (BIM) has been the primary step toward technological advancement in the UK construction industry which helped construction professionals to review and evaluate the improvement potential of the industry (Barlish and Sullivan, 2012). Since then, many technology-driven safety management systems (SMS) have been proposed by safety experts by introducing several technologies. In fact, since the advancement in technology, there has hardly been a safety management system (SMS) proposed without technological involvement. Table 2.4 below lists a few of the technology-driven safety management systems below.

Apart from the effectiveness of the technology-driven safety management systems, these management systems do not comprise the holistic safety management approach but have rather built on a specific domain. For instance, Giretti et al. (2009) developed a system using advanced augmented reality technology for the safety inspection and workers monitoring, however, doesn't assist with safety planning and management. Similarly, Guo, Li and Li (2013) proposed a comprehensive conceptual framework based on virtual technology for safety planning, hazard identification and training but did not include the safety monitoring part to fulfil the definition of a safety management system driven by HSE. Hence, most SMSs based on advanced technology do not offer inclusive safety management however, they serve a specific purpose.

Table 2.4: Technology-Driven Safety Management Systems

Author	Title
(Giretti *et al.*, 2009)	Design and First Development of an augmented real-time safety management system
(Guo, Li and Li, 2013a)	VP-based safety management system in large-scale construction projects: A conceptual framework
(Hu and Zhang, 2011)	BIM and 4D-based integrated solutions of analysis and management for the conflict and structural problems during construction
(Zhang *et al.*, 2015a)	BIM-based fall hazard identification and prevention in construction safety planning
(Awolusi, Marks and Hallowell, 2018)	Wearable technology for personalized safety monitoring and trending
(Teizer, Cheng and Fang, 2013b)	Location tracking and data visualization technology to advance construction ironworkers' education and training in safety and productivity
(Le *et al.*, 2015a)	A framework for using mobile-based virtual reality and augmented reality for experiential construction safety education
(Chantawit *et al.*, 2005a)	4DCAD-Safety: Visualizing project scheduling and safety planning
(Melo *et al.*, 2017a)	Applicability of unmanned aerial system (UAS) for a safety inspection on construction sites
(Bansal, 2011a)	Application of geographic information systems in construction safety planning

Similarly, management-driven safety management systems have their limitations as they are built to overcome the specific factors/indicator or developed for a specific need. For example, Guo, Yiu and González (2015) developed a system to help mitigate the impact of behavioural factors, however, do not comply with other key factors. Similarly, Maiti and Choi (2021) proposed a safety management framework for safety planning based on the existing knowledge and promoted collaborative working for safety management but the framework was limited to safety planning and do not offer assistance towards other aspects of safety. Hence, the literature revealed that the existing safety management systems assist construction professionals to some extent but don’t comply with the key safety factors. For robust safety management, it is therefore essential to explore and evaluate all the factors which affect or influence safety management during the construction project.

2.5. Factors Affecting Safety Management

Over the last decade, researchers have been particularly concerned with safety management in the construction industry. After reviewing 513 articles in the construction safety domain, Jin et al. (2019) discovered that the safety management programme has been a topic of interest for researchers in the previous decade. The process of managing safety standards, practices, and procedures on a construction site is known as construction safety management. Abas et al. (2020). Safety management practices, in addition to safety regulations, play an important role in safety management. According to the literature, traditional H&S practice is divided into two phases: the pre-construction phase, during which safety is planned and the construction (second) phase, during which safety is executed, and monitored. Zhang et al.(2013a). However, many researchers also mentioned that contemporary safety practices rely immensely on human perception, experience, knowledge, and cognitive capabilities to identify hazardous situations (Hongling *et al.*, 2016; Wang, Zou and Li, 2016; Nawaz *et al.*, 2020). Carter and Smith (2006) claimed that hazard identification by workers' cognitive aptitudes is impossible due to the dynamic, unpredictable nature and uniqueness of construction sites. Failure to identify safety hazards is the key cause of accidents in the construction industry (Guo, Yu and Skitmore, 2017b). Therefore, it is essential to explore possible safety factors that could cause an incident or an injury on the construction site.

Various construction industry researchers have investigated safety management performance and unearthed previously unknown aspects influencing H&S management. For instance, Hare, Cameron and Roy Duff (2006) mentioned that adequate safety planning is one of the most significant things that can play a critical part in any construction project's success. Azhar (2017) believes that health and safety planning is still done separately from project planning and that this lack of integration could result in an accident during construction. Workers are more vulnerable to unforeseen dangers and can suffer catastrophic damage when hazard identification is not fully analysed with project design (Albert *et al.*, 2014). As a result, integrated H&S planning is recognised as one of the variables that could lead to mortality.

Hazard identification is a vital aspect of safety management, and the capacity to detect possible dangers on construction sites before beginning actual work is a critical factor in mitigating risks (Eiris, Gheisari and Esmaeili, 2018). Similarly, worker training, safety culture, safety behaviour, risk assessment, stakeholder relationships, safety resource allocation, and the complexity of construction projects as some of the well-known variables contributing to inadequate safety management as cited by several scholars (Zou, Zhang and Wang, 2007; Ismail *et al.*, 2012; Agumba and Haupt, 2014; Jafari, Gharari and Kalantari, 2014; Xia *et al.*, 2018; Wang *et al.*, 2019). There has been a lot of research on safety factors by researchers all over the world, either unique to their countries or projects, but no comprehensive approach to figuring out all conceivable safety elements in the construction sector has been taken. As a result, this study will take a methodical approach to review the current literature on factors affecting safety management and develop an SMS framework to reduce all of the risks involved.

2.6. Literature Analysis

After the selection of pertinent state-of-the-art literature from peer-reviewed journals, the analysis was done in three stages. In the first stage, the empirical analysis has been performed with NVivo 12 Pro using the word frequency function on the selected articles to conceptualize the safety factors taxonomy. The minimum letter length was set to “Four (4) Letters” and grouping criteria were set to ‘Exact Match’ for the word frequency test to get the most appropriate blend of words called ‘safety concepts’ from the literature. Table 2.5 and Figure 2.14 show the result of the word frequency test identifying all the safety concepts related to H&S management.

Table 2.5: Safety Concepts Count and Weight (%)

Words	Count	Weighted Percentage (%)
management	4764	1.22
risk	2558	0.65
workers	2333	0.60
site	1439	0.37
data	1389	0.35
training	1369	0.35
climate	1245	0.32
design	1052	0.27
culture	854	0.22
assessment	811	0.21
contractors	781	0.20
practices	742	0.19
environment	708	0.18
quality	704	0.18
time	696	0.18
equipment	691	0.18
information	671	0.17
cost	659	0.17
experience	625	0.16
unsafe	612	0.16
behaviour	599	0.15
method	587	0.15
planning	567	0.14
implementation	548	0.14
knowledge	545	0.14
productivity	508	0.13
workplace	500	0.13
approach	479	0.12
hazards	474	0.12
relationship	448	0.11
human	440	0.11
commitment	432	0.11
measures	431	0.11
technology	428	0.11
communication	422	0.11
systems	420	0.11
education	415	0.11
activities	404	0.10
regulations	404	0.10
organization	396	0.10
compliance	395	0.10
tools	371	0.09
perception	354	0.09
indicators	353	0.09

procedures	353	0.09
resources	338	0.09
policy	325	0.08
supervisors	321	0.08
materials	318	0.08
awareness	307	0.08
decision	307	0.08
attitude	299	0.08
social	297	0.08
understanding	285	0.07
involvement	283	0.07
motivation	266	0.07
stakeholders	266	0.07
technologies	265	0.07
plan	262	0.07
responsibility	259	0.07
audit	258	0.07

Figure 2.14: Safety Concepts

Subsequently, the clustering has been performed after contextualizing the safety concepts (Table 6) generated by the word frequency test to categorize them into numerous groups. The clustering performed was based on the comparative study of the context of the words generated by the empirical study. The analysis indicated that these concepts can be interpreted into six different clusters namely ‘organisational’, ‘managerial’, ‘legislative’, ‘social’, ‘environmental’ and ‘personnel’. It has also been indicated that most of these concepts can be interpreted in multiple groups. For instance, a word like ‘management’, can be linked to the ‘organisational’, 'managerial', 'legislative', 'environmental' and 'personnel' groups. Figure 2.15 shows the cluster analysis of the complete list of safety concepts based on their safety context.

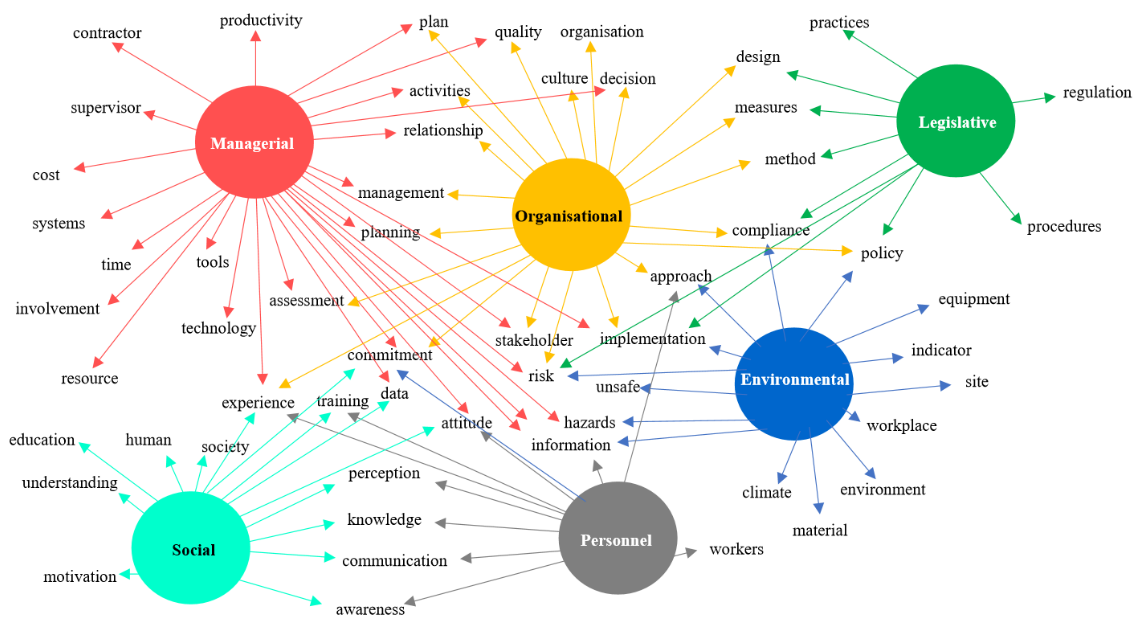

Figure 2.15: Cluster Analysis of Safety Concepts

Furthermore, the cluster analysis also indicated that many of the concepts were interlinked and phrased as H&S management factors when combined. For instance, the word 'hazard' and 'perception' together exhibit adequate H&S management factors cited by many researchers (Khosravi *et al.*, 2014; Wang, Zou and Li, 2016; Durdyev *et al.*, 2017; Gunduz and Laitinen, 2017; Gul, 2018; Machfudiyanto, Latief and Robert, 2019; Othman *et al.*, 2020). Therefore, in the second stage, another empirical analysis was performed to formulate the H&S management factors associated with the safety concepts generated in stage one. Each of the safety concepts was analysed separately with NVivo 12Pro Text Search function using the selected literature and a list of sixty-three H&S management factors was compiled in six different clusters. Moreover, as aforesaid the analysis revealed that several factors are linked with multiple clusters and can only be mitigated if managed in all related clusters, for instance, safety perception is a part of organisations, managerial and personnel clusters. Therefore, some of the safety factors were listed in multiple clusters in the safety factors table. Table 2.6 shows the list of all contributory H&S management factors found in the literature.

Table 2.6: H&S management Factors

Organisational		
F1 F2 F3 F4 F5 F6 F7 F8 F9 F10 F11 F12 F13 F14 F15	Safety Management Policy design Safety audit Safety culture Commitment Approach Safety Perception Implementation plan Safety compliance Information management Structure & Responsibilities Stakeholders management Resource management Quality Economics	(Haslam *et al.*, 2005)(Hallowell, 2012)(Zhou, Goh and Li, 2015)(Aksorn and Hadikusumo, 2008) (Wang, Zou and Li, 2016)(Li, Ning and Chen, 2018)(Ismail, Doostdar and Harun, 2012)(Gao *et al.*, 2018)(Durdyev *et al.*, 2017) (Jaafar *et al.*, 2018)(Gunduz and Ahsan, 2018)(Pereira *et al.*, 2020)
Managerial		
F16 F17 F18 F19 F20 F21 F22 F23 F24 F25 F26 F27 F28 F29 F30 F31 F32 F33 F34 F35 F36 F37	Safety planning Safety management system Training Safety cost design Safety compliance Decision making Communication Knowledge sharing Safety Education Commitment to Safety Safety attitude Safety culture Safety perception Contractor experience Supervision & monitoring Enforcement Safety Tools/technology Safety meetings Risk Assessment Hazard identification Data Sharing Safety investment/incentives	(Othman *et al.*, 2020)(Khosravi *et al.*, 2014)(Aksorn and Hadikusumo, 2008) (Haslam *et al.*, 2005)(Wang, Zou and Li, 2016)(Al Haadir and Panuwatwanich, 2011)(Gunduz and Ahsan, 2018)(Wang, Zou and Li, 2016)(Aksorn and Hadikusumo, 2007a)(Park and Kim, 2013a)(Pereira *et al.*, 2020)(Jaafar *et al.*, 2018)(Gul, 2018)(Gao *et al.*, 2018)(Durdyev *et al.*, 2017)(Zahoor *et al.*, 2017)(Nawaz *et al.*, 2020)(Mohammadi, Tavakolan and Khosravi, 2018a)(Abas *et al.*, 2020)(Al Haadir and Panuwatwanich, 2011)(Ismail, Doostdar and Harun, 2012)(Durdyev *et al.*, 2017)(Mathar *et al.*, 2020)(Mollo, Emuze and Smallwood, 2019)(Zhou, Goh and Li, 2015) (Li, Ning and Chen, 2018) (Hallowell, 2012)(Gunduz and Ahsan, 2018)
Legislative		
F38 F39 F40 F41 F42 F43	Safety code Compliance Safety policy Safety methods Commitment to regulation Enforcement plan	(Zhou, Goh and Li, 2015) (Wang, Zou and Li, 2016)(Aksorn and Hadikusumo, 2008)(Li, Ning and Chen, 2018) (Durdyev *et al.*, 2017) (Hallowell, 2012) (Gao *et al.*, 2018)(Pereira *et al.*, 2020)(Ismail, Doostdar and Harun, 2012)

Social		
F44 F45 F46 F47 F48	Society culture Workers ethnicity Education & Commitment Safety perception Awareness & Motivation	(Zhou, Goh and Li, 2015) (Wang, Zou and Li, 2016)(Li, Ning and Chen, 2018)(Aksorn and Hadikusumo, 2008)(Li, Ning and Chen, 2018) (Pereira *et al.*, 2020)(Durdyev *et al.*, 2017) (Hallowell, 2012) (Gao *et al.*, 2018) (Gunduz and Ahsan, 2018) (Ismail, Doostdar and Harun, 2012)
Environmental		
F49 F50 F51 F52 F53 F54 F55 F56	Construction site Unsafe climate Safety hazards Safety indicators Unseen risks Equipment & materials Uncontrolled conditions Weather	(Zhou, Goh and Li, 2015)(Hu *et al.*, 2011)(Li, Ning and Chen, 2018) (Hallowell, 2012) (Gao *et al.*, 2018) (Wang, Zou and Li, 2016) (Ismail, Doostdar and Harun, 2012) (Durdyev *et al.*, 2017) (Pereira *et al.*, 2020)(Gunduz and Ahsan, 2018) (Jaafar *et al.*, 2018)
Personnel		
F57 F58 F59 F60 F61 F62 F63	Attitude Risk awareness Education Safety Perception Commitment to plan Hazard perception Training	(Wang, Zou and Li, 2016)(Zhou, Goh and Li, 2015)(Li, Ning and Chen, 2018)(Hu *et al.*, 2011) (Gunduz and Ahsan, 2018) (Pereira *et al.*, 2020)(Li, Ning and Chen, 2018)(Li, Ning and Chen, 2018) (Hallowell, 2012) (Gao *et al.*, 2018) (Ismail, Doostdar and Harun, 2012) (Durdyev *et al.*, 2017)

Figure 2.16 illustrates six H&S management clusters developed in stage 2 of the research.

Figure 2.16: H&S Factor Clusters

2.7. Safety Management System Framework Development

A safety management system (SMS) framework is defined by HSE and international standards as a systematic and proactive approach to managing safety policies and procedures to mitigate the risks involved in the project. After the formulation and clustering of H&S factors, the third and final phase of research intended to propose an SMS framework aligned with all the associated H&S management clusters found in stage 2 of the empirical analysis. The proposed framework showcases the relationship between safety factors and safety drivers to better understand and manage the safety factors which if unattended lead to incidents on site. The adequate implementation of the SMS framework improves safety performance by taking into account the safety factors and eventually leading to the success of the project. In this phase, the proposed SMS framework was developed in three tiers to develop a methodical approach to mitigate and manage all H&S factors. The tier-one routes all the safety factors through two drivers; 'Safety Administration' and 'Information Technology (IT) Adoption' listed in Table 2.7.

Table 2.7: Safety Factors Classification

Safety Administration	IT Adoption
Program/Planning	Technology/tools/innovation
Legislation/policy/method	Communication/information/data-sharing
Competence/ Knowledge	Planning/programming
Compliance/Implementation	Training/education
Contractor/supervisor experience	Hazard identification/risk assessment
Leadership/commitment	Monitoring/supervision
Stakeholders/team management	Equipment/site mapping
Roles/responsibilities	Attitude/culture/perception/awareness
Resources/safety cost	
incentives/motivation	
Environment/equipment/materials	

Table 2.8: Researchers Endorsing Safety Administration & IT as Safety Drivers

Safety Driver	Author
Safety Administration	(Machfudiyanto, Latief and Robert, 2019)(Ismail *et al.*, 2012), (Choudhry, 2017)(Wachter and Yorio, 2014)(Fang, Chen and Wong, 2006a)(Zhou, Fang and Wang, 2008; Åsgård and Jørgensen, 2019), (Chileshe and Dzisi, 2012)(De Snoo, Van Wezel and Jorna, 2011)(Li, Ning and Chen, 2018)(Othman *et al.*, 2020)(Khosravi *et al.*, 2014)(Aksorn and Hadikusumo, 2008)(Haslam *et al.*, 2005)(Wang, Zou and Li, 2016)(Al Haadir and Panuwatwanich, 2011)(Gunduz and Ahsan, 2018)(Wang, Zou and Li, 2016)(Aksorn and Hadikusumo, 2007a)(Pereira *et al.*, 2020)(Jaafar *et al.*, 2018)(Gul, 2018)
IT Adoption	(Benjaoran and Bhokha, 2010)(Zhang *et al.*, 2015a)(Choe and Leite, 2017)(Frank Moore and Gheisari, 2019a)(Zhou and Ding, 2017)(Bansal, 2011a)(Zhang, Shi and Yang, 2020)(Park and Kim, 2013a)(Carter and Smith, 2006b)(Melo *et al.*, 2017a)(Ganah and John, 2017)(Rwamamara *et al.*, 2010)(Balgheeth, 2016)

H&S literature explicitly illustrates the use of two drivers as safety management and risk mitigation techniques. These drivers were formed based on a thorough literature review which on one side states that managing safety policies and procedures defines the SMS framework, however, a wealth of literature also argues intensely on the adoption of information technologies for safety performance promotion and risk assessment for improved safety performance. For instance, Table 2.8 above shows the number of researchers' work endorsing 'Safety Administration' and different 'IT' technologies for a certain aspect of safety management. Figure 2.17 shows the SMS framework developed in three tiers considering all the safety factors.

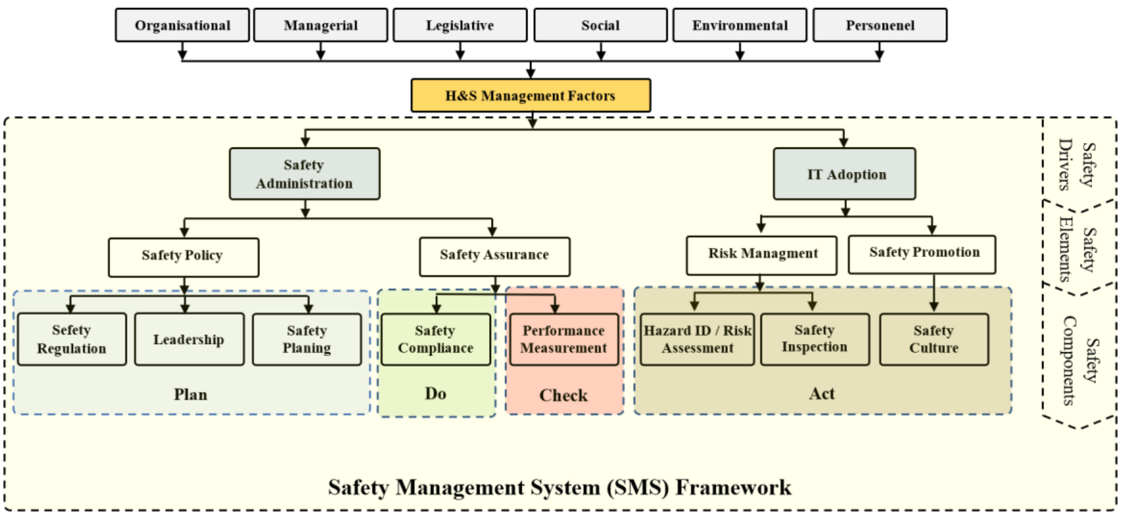

Figure 2.17: Safety Management System (SMS) Framework

After defining the drivers of the SMS, tier-two comprises the four elements of safety management recommended by OSHA and ISO safety standards to include every aspect of safety management. The four elements derived were; ‘safety policy’, ‘safety assurance’, ‘risk management, and ‘safety promotion’ which imitates the basic elements of a safety management system i.e. planning, implementation, education and inspection. The categorization of safety elements into two safety drivers demonstrates safety management from the top level in the organization. Tier three further narrows down each safety element to safety components involved in the planning of that element for better understanding and control of safety. This tier indicates all the essential components entailed in the accomplishment of an effective SMS framework. These essential components include: ‘safety regulations’, ‘leadership’, ‘safety planning’, ‘safety compliance’, ‘performance measurement’, ‘hazard identification/risk assessment’, ‘safety inspection’, and ‘safety culture’. Each of these components is discussed in detail and the relationship between safety components and safety factors is explained in section 2.7.1. The discussion on each of the safety components highlights how safety factors are connected with safety components and validate the SMS framework from the literature review.

2.7.1. Results and Discussion

2.7.1.1. Safety Policy

The safety policy statement is the essential part of the SMS framework which states the organisation’s beliefs on fundamental regulations, commitment and responsibilities regarding health and safety management (Ismail *et al.*, 2012). A successful safety policy not only leads to the success of safety objectives but also manifests the success of an organisation's overall mission. Hence, the success of a safety policy depends on:

2.7.1.1.1. Safety Regulations

Safety regulations are one of the decisive factors found in the research towards the successful implementation of health and safety. Many countries have implemented their H&S regulations such as the Occupational Safety and Health Administration (OSHA 2013) in the United States, British Standards Institute (BSI 2000) (Choudhry, 2017). As aforementioned, the CDM regulations 2007 development by the government commission was a big milestone in terms of safety management. The safety regulations provide essential guidelines for safety management practices to accomplish positive safety results (Wachter and Yorio, 2014). Organisational values and culture have a direct impact on the successful implementation of safety regulations (Gao *et al.*, 2018). Although safety management regulations play important role in managing safety, however, the extensive research on H&S factors revealed that successful application of the safety regulations can only be achieved by taking into account; organisational factors, safety compliance methods, and managerial factors (Gunduz and Ahsan, 2018). Figure 2.18 below demonstrates each of the factors of safety regulations broken down into the contributing attributes of each factor.

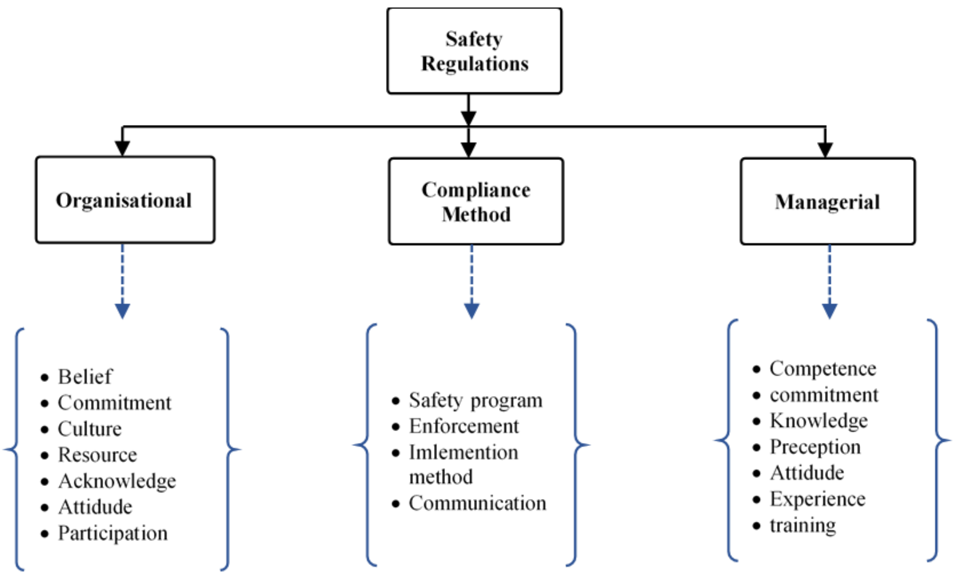

Figure 2.18: Safety Regulation Factors

2.7.1.1.2. Leadership

The consequentiality of safety culture has long been discussed in the safety literature and is perceived as the evolving safety values, perceptions and attitudes of employees to improve the safety performance within the organisation (Fang, Chen and Wong, 2006a). The leadership has the core commitment and responsibility toward developing a safety culture that leads toward a positive impact on the workers and improved safety performance (Umar, 2020). Moreover, the leadership has a direct role in defining safety policies, risk assessment, programme development, implementation plans, and evaluation (Li, Ning and Chen, 2018). The personal involvement of top leadership in safety planning and execution is recognized as the key component of safety management to achieve safety performance in the organisation (Machfudiyanto, Latief and Robert, 2019). The safety regulations and plans do not lead to success without competent leadership. Khdair (2011) also stated that leadership attitude is a decisive factor in achieving safety goals.

Nevertheless, the critical analysis of safety factors illustrates the significance of leadership and the related success attributes. Safety attitude and commitment are found to be the key factors of effective leadership. Figure 2.19 below demonstrates each of the factors of safety regulations broken down into the contributing traits of each factor.

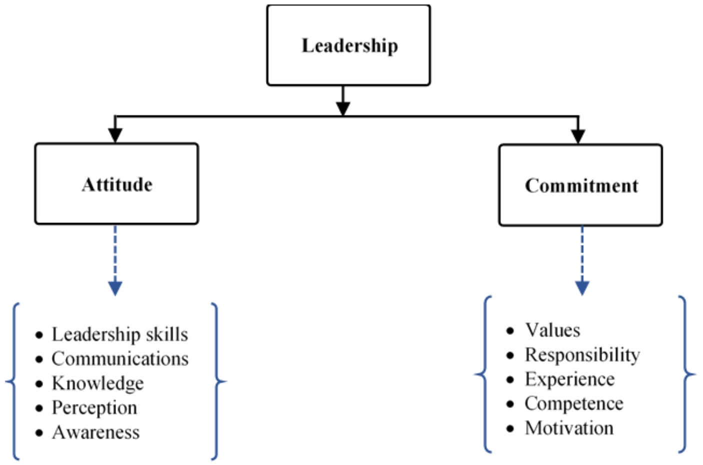

Figure 2.19: Leadership Factors

2.7.1.1.3. Safety Planning

Effective safety planning is recognized as one of the important factors that play a vital role in the success of any construction project (Hare, 2006). It is recognized as a two-stage process: planning and implementation (Zhang *et al.*, 2013a). Risk assessment and hazard identification are the essential parts of safety planning that need to be done at the pre-construction stage. The ability to identify the potential hazards on construction sites before initiating the actual work is a decisive part of the safety plan to mitigate the risks (Eiris, Gheisari and Esmaeili, 2018). It doesn't only contribute to the prevention of accidents but also deters the ill health of the workers on construction sites (Bansal, 2011b). Subsequently, safety planning also needs to consider at the earliest stages of project planning to mitigate the safety issues and relevant risks. The decisions made during the planning phase have an immense impact on the successful completion of the project (De Snoo, Van Wezel and Jorna, 2011).

One of the contributory factors of impaired safety performance is conducting safety planning separately from project planning and considered the sole contractor's responsibility (Chantawit *et al.*, 2005b). Efforts have been made in the past to integrate safety planning with project design, scheduling and cost planning to improve safety performance proactively. The construction CDM regulation (2007) in this regard provides the most integrated safety planning approach as well as involves every stakeholder in the safety planning process. It explicitly defines roles and responsibilities for everyone involved in the design and construction planning process during the pre-construction phase of the project (Zhou, Whyte and Sacks, 2012). The detailed analysis of safety factors highlighted safety planning as a substantial factor contributing to H&S management. Figure 2.20 below demonstrates each of the factors of safety planning broken down into contributing traits.

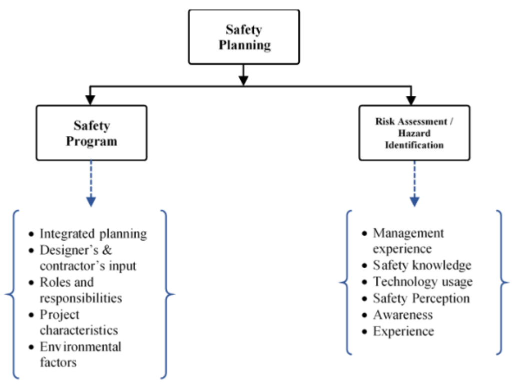

Figure 2.20: Safety Planning Factors

2.7.1.2. Safety Assurance

Safety assurance is at the core of the safety management system that ensures the implementation of the systematic safety plan and continuous surveillance of safety performance throughout development. In the construction industry, safety implementation starts with the application of safety regulations in the design and planning stages followed up by continuous inspection and monitoring during the construction phase of the task. The two aspects of safety implementation identified in the literature review are;

2.7.1.2.1. Safety Compliance

Safety compliance in the construction industry is adhering to the safety procedures to carry out the work in the safest possible way (Zhou, Fang and Wang, 2008). The success of the safety management system depends momentously on the safety implementation plan. The research revealed that the good implementation of the safety management system enables the organisation to meet the safety as well as the overall project goals (Chileshe and Dzisi, 2012). In the United Kingdom, CDM regulations provide the key steps for the implementation of a safety management system that includes: (1) safety protective measures, (2) the use of rights safety tools, (3) providing training and instructions (4) effective supervision (CDM, 2015). There is also a wealth of literature on safety implementation, the essential elements found in the literature are; proactive safety programs, directions, education and training, clear roles and responsibilities and review methods. A vital factor of a successful implementation program is to periodically educate and train the workers to improve their knowledge as well as their safety awareness (Bavafa, Mahdiyar and Marsono, 2018). Clear roles and responsibilities enable the management team to mitigate the potential risks and eventually accidents on construction sites (Yu *et al.*, 2014). Figure 2.21 below demonstrates each of the factors of safety implementation broken down into the contributing traits of each factor.

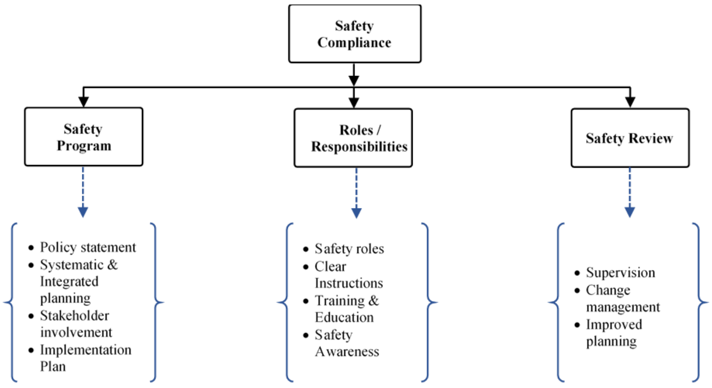

Figure 2.21: Safety Compliance Factors

2.7.1.2.2. Performance Measurement

The performance of any safety management system inevitably depends on continuous safety monitoring and review for the improvement of the system. It is recognised as an integral part of the safety management system that reflects success through continuous review and change management. Although the safety regulations enforced by the government around the globe set a self-regulatory approach to measuring safety performance, however, construction professionals advocate for a personalised safety performance measurement framework. Williams, Fugar and Adinyira (2019) stated that hazard identification, monitoring and evaluation, and safety encouragement are the essential traits to be considered for safety performance measurement. The analysis of extensive literature revealed the following as the factors of safety measurement; development of the supervisory team, monitoring of compliance, communication with the site workers, and participation in safety (Ng, Cheng and Skitmore, 2005). The supervisory personnel qualification, experience, knowledge, safety awareness, training and commitment have a significant impact on performance measurement. Figure 2.22 below shows the factors of performance measurement.

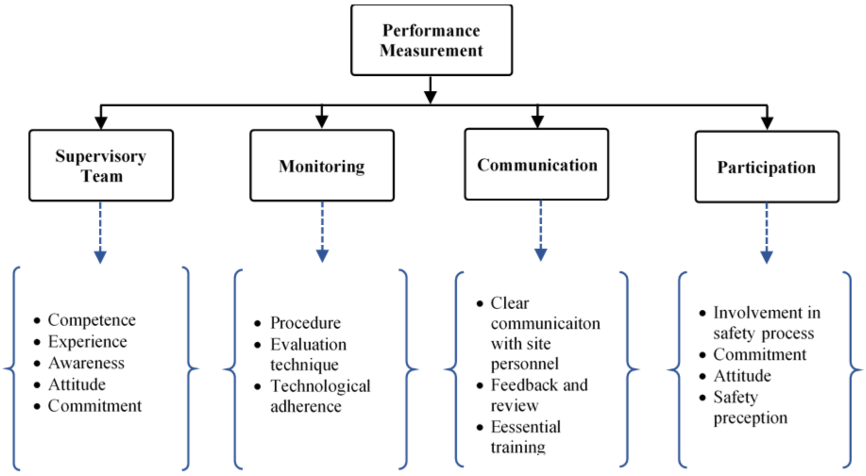

Figure 2.22: Performance Measurement Factors

2.7.1.3. Risk Management

Risk management is recognized as identifying and controlling the safety risks in the construction process to help the organisation meet its time, quality and financial goals (Serpella *et al.*, 2014a). The literature shows that this is one of the most important parts of the safety management system is risk identification and analysis. The decision made on the identified risks has an immense impact on the project's overall performance. The risks are managed in two stages; at the pre-construction stage risks are identified and controlled during the design and planning phases, secondly, during the construction stage, site inspections are carried out to mitigate potential risks. Therefore, two characteristics of risk management are;

2.7.1.3.1. Risk Assessment

Risk assessment is recognized as a critical procedure of safety planning as it involves identifying the potential risks that could cause harm to the site personnel (Karimiazari *et al.*, 2011). Identifying and managing the risk from the initial stages of planning, procurement until the construction, and handover is significantly essential to completing the project on time, cost and quality. The researchers have highlighted the importance of systematic risk assessment methods for efficient and effective risk management and planning (Serpella *et al.*, 2014b). The lack of an effective risk assessment method could lead to several issues during the project. For example, the ineffective risk assessment against the potential hazard or miscommunication could lead to unforeseen events on the construction site, delays, an increase in cost or disputes among the parties. The extensive literature review on safety factors revealed that the safety manager's knowledge and experience can have a positive impact on risk assessment. Another factor that helped safety managers to identify and analyse safety risks is the use of information technology. The use of building information modelling (BIM) has not only helped to identify the safety risks in the pre-construction phase but also lessened the dependency on human perception and knowledge of risk assessment. Figure 2.23 below shows the factors involved in risk assessment.

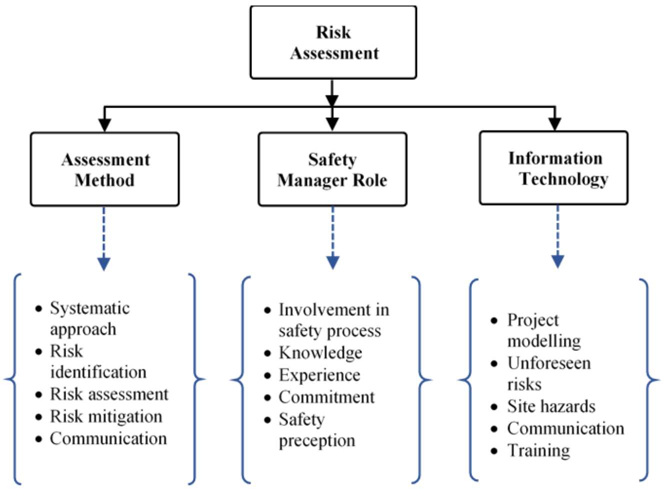

Figure 2.23: Risk Assessment Drivers

2.7.1.3.2. Safety Inspection

The site inspection is another essential element of a safety management system and an adequate way to monitor the risks involved, tasks/activities progress, tasks duration, working environment, people and equipment involved in the construction process. One of the research done in China on health and safety management ranked safety inspection as the top third factor affecting safety management (Ashebir *et al.*, 2020). To ensure compliance with the Construction (Design and Management) Regulations (CDM), the principal contractor is bound to arrange an efficient mechanism for regular safety monitoring. The internal inspections are carried out by the contractor or a third-party audit to make the construction process safe and productive. Health and Safety inspection is essential for any task that involves risk as they are the source of accidents, such as work at height, fall protection system, PPE, equipment on the site, scaffold, structural stability and unauthorized access to the site.

In the traditional safety inspection process, manual observations are usually carried out by a safety supervisor or safety specialist on the construction site and after analysis, necessary precautions are considered (Hinze, Thurman and Wehle, 2013). However, with the advancement in information technology, new technologies for inspection have been introduced by construction professionals. For instance, Tsai, Hsieh and Kang (2014) presented a BIM technology for the construction site inspection using the site images generated by BIM. Ashour et al. (2016) used drone technology for gathering site data by taking images at regular intervals. Similarly, Melo et al. (2017) introduced Unmanned Arial Vehicles (UAVs) for construction site monitoring with enhanced visualization capability. Nevertheless, from the literature review, it is deemed that site inspection should be carried out frequently by a competent safety supervisor based on the safety policy and utilizing the latest technologies that help to identify the hazards precisely (Irizarry, Gheisari and Walker, 2012b). Figure 2.24 below shows the essential drivers of safety inspection.

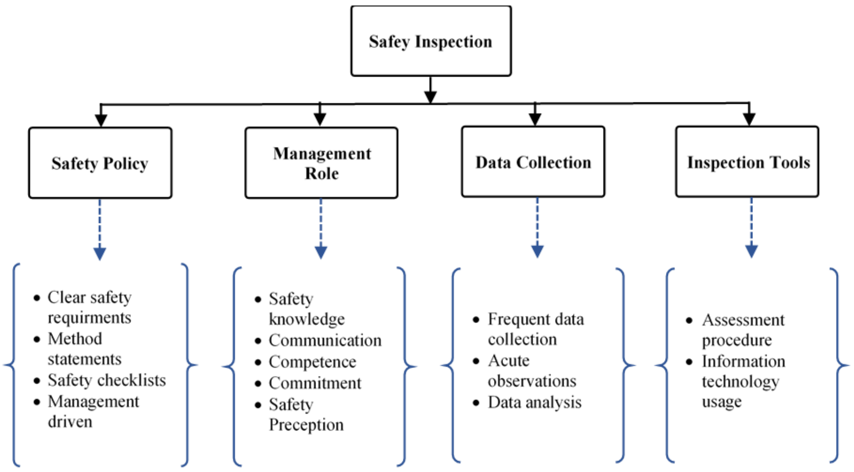

Figure 2.24: Safety Inspection Management

2.7.1.4. Safety Promotion

Safety promotion is the core of any safety management system as it aims to develop and maintain the safety conditions at the construction site by management, site personnel and everyone involved in the development process. The success of any safety management system is at stake without an effective safety promotion policy. The critical drivers of safety promotions found in the literature are safety culture in the organisation.

2.7.1.4.1. Safety Culture

The terms ‘safety culture’ captured the attention of safety experts from different industries involved in the dangers occurring, such as the construction industry which is well-known for accidents. The safety culture is defined by professionals as an outlook of collective beliefs, values, attitudes and behaviours on safety set by an organisation on its entire hierarchy to minimize the exposure to a condition that can cause accident or injury to the members of the organisation (Fung *et al.*, 2005). The wealth of literature on safety culture recognizes it as a leading indicator of the safety management system that helps organisations to reduce the number of accidents on construction sites (Khawam and Bostain, 2019). Subsequently, Hallowell et al. (2013) argued that a safety culture is one of the most important investments for employees as it increases employee awareness and knowledge of safety conditions.

Cooper (2000) conceptualized safety culture in three interrelated aspects: psychological, behavioural and situational aspects. The psychological aspect referred to the organisational values, attitudes and perceptions, the behavioural aspect describes the personal behaviours towards safety, whereas, situational aspects are concerned with the organisational policies, regulations and safety management system. A reputable fact from the research is that the behavioural and psychological aspects of a safety culture can be dealt with through adequate training and education programmes (Tudoreanu, no date; Wilkins, 2011). Moreover, the use of information communication technologies (ICT) has improved the learning capability of trainees by creating real-world scenarios and more visualized learning methods. For instance, virtual reality (VR), Augmented Reality (AR) and other vision-based technologies are quite famous in the construction industry for training purposes (Tudoreanu, no date; Zhao and Lucas, 2015a; Li *et al.*, 2018b).

Considering the Cooper (2000) model of safety culture, several researchers have explored the factors involved to achieve a safety culture at the maximum capacity. Research on safety culture improvement by Machfudiyanto, Latief and Robert (2019) regarded leadership, safety behaviour, and perception as crucial factors of safety culture. Similarly, another research stated leadership, safety training, commitment and resource allocation as the factors affecting safety culture (Ismail *et al.*, 2009). Figure 2.25 below shows the factors involved in the achievement of a safety culture. Whereas, Figure 2.26 conceptualizes the proposed SMS framework that presents Safety Components with relevant safety factors.

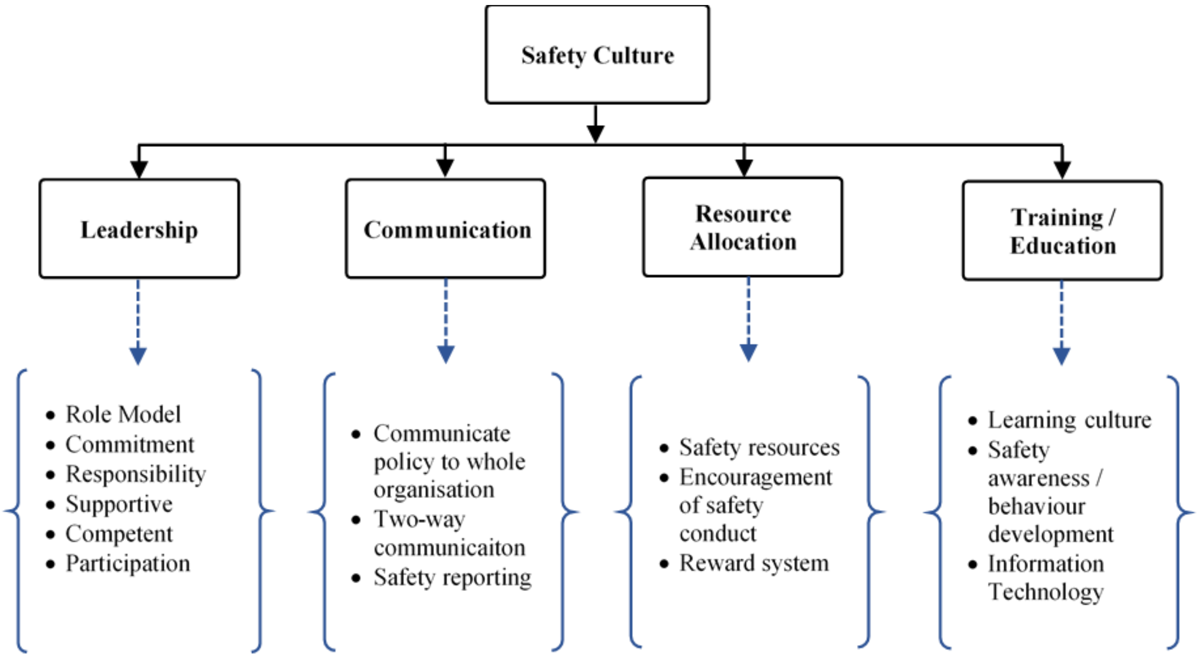

Figure 2.25: Safety Culture Adoption

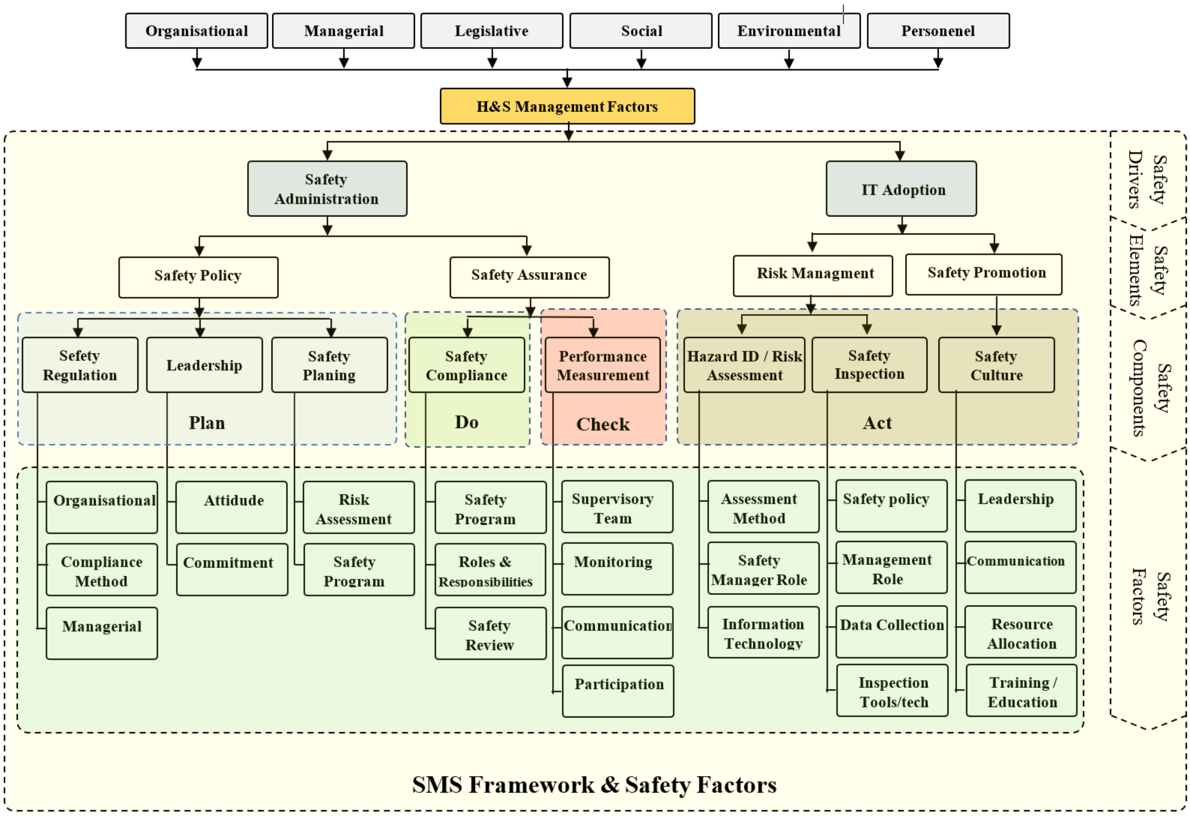

Figure 2.26: SMS Framework illustrating Safety Factors with Safety Components

2.8. Chapter Summary

Accidents on construction sites leading to fatalities, serious injuries and economic costs are a great concern for the construction industry. The pragmatic approach has been used for the research intended to create a Safety Management System framework to improve the safety performance of construction projects. Therefore, the research is immersed into the safety literature to get an in-depth insight into the occupational health and safety factors involved in the SMS of a construction project to develop a robust safety management framework that complies with all safety factors. This objective was achieved by undertaking an empirical study and a list of sixty-three safety factors was identified from the literature review and classified into six clusters. It has been found that the effective SMS framework requires an inclusive approach to organisational, managerial, legislative, environmental, social, and personnel safety factors to strive for better safety performance.

Hence, the research also proposed to develop an SMS framework to comprehensively analyse and manage the safety performance taking into account the safety factors. Therefore, for adequate safety implementation, the study proposed a safety management system framework developed in three tiers to cope with all safety factors involved in safety management. The first and primary tier called ‘Safety Drivers’ channelizes the safety management into two corridors namely ‘Administrative’ and ‘IT’. The administrative route emphasizes safety policy development and assurance, the IT oversees risk management and safety promotions which are called the ‘Safety Elements’ of the SMS framework. To ensure the success as well as the effectiveness of the SMS framework, another tier was added to the SMS framework called ‘Safety Components’. The tier consists of essential steps involved in safety management and reflects the typical safety management system (plan, do, act and check). Furthermore, the safety factors associated with each safety component have been illustrated in the SMS framework which helps safety managers to consider safety factors for robust safety management.

Chapter 3: Human Factor and Elimination Techniques

3. Introduction

The previous reviewed the factors affecting H&S as well as developed the initial framework based on empirical research. This chapter explores the factors having significant impacts on safety performance. Furthermore, an extensive literature review on the methods and techniques to overcome those factors in different industries along with the construction industry will be carried out in pursuit to develop a robust method/framework to mitigate the impact of the underlined factors.

3.1. Outstanding Factors causing Accidents in Construction Industry

Researchers in recent years have given considerable attention to finding out the causal factors responsible for the accidents (Hu *et al.*, 2011; Mohammadi, Tavakolan and Khosravi, 2018a; Machfudiyanto, Latief and Robert, 2019). There are several reasons for the accident to happen as a result of some factors in the workplace (Hoła *et al.*, 2017). According to the literature, current safety management approaches focus mainly on managing the organisational, managerial and environmental factors. However, accident causation studies have shown that about 80-90% of accidents happen as a result of human error (Baysari *et al.*, 2009; Guo, Yiu and González, 2016; Fan *et al.*, 2020). Moreover, Reason (1990b) claimed human error is a predominant cause of accidents that happens if the human factor is not considered in safety management. Similarly, several accident causation studies have mentioned human failure as the main cause of accidents (Kariuki and Löwe, 2007). Hinze, Pedersen and Fredley (1998) stated that accident prevention can only be achieved with a clear understanding of root causes. Hence, the integration of human factors into the safety management system is therefore essential for accident prevention and inherent safety management (Kariuki and Löwe, 2007). More emphasis needs to be given to human error if accidents are to be reduced (Groth and Mosleh, 2012; Hosseinian and Torghabeh, 2012; Winge, Albrechtsen and Mostue, 2019; Milazzo, Ancione and Consolo, 2021).

3.2. Human Factor

Humans are the core, adaptable and flexible part of any working system and yet most vulnerable (Nair, 2015; Edmonds, 2016c). Human actions are considered important contributors to the health and safety performance of industries (Manu, 2013). Rigby (1970) first cited human error as a series of human actions that exceed the limits of acceptability (Hosseinian and Torghabeh, 2012). As most accidents in the construction industry are the result of human errors, the consensus among safety researchers has been developed on the human factor as the main reason behind accidents (Suraji and Duff, 2000; Habibi and Pouya, 2015; Jin *et al.*, 2019; Winge, Albrechtsen and Mostue, 2019; Ünal *et al.*, 2021). Within any workplace, the term 'Human Factor' is usually described as the interaction of human beings with each other and the workplace (Milazzo, Ancione and Consolo, 2021). Until recently, HSC defined the human factor as "The environmental, organisational, job factors, and individual characteristics which influence behaviour at the work in a way which can affect health and safety" (HSC, 2005).

Edmonds (2016b) represented the interaction of humans with other characteristics of the system with the web called 'human within the work system. This represents the interaction of people with their surroundings that including hardware, software, work and social environment within the workplace shown in Figure 3.1 below. The critical factors mentioned on the web are Work tasks, Work Equipment, Work tools, Workplace, Organisational context and Environment context which according to Edmonds (2016) should be considered to manage human factors. Similarly, many researchers have noted the significance of the human factor knowing its catastrophic impacts if left unattended. Therefore the need to consider the human factor in the safety assessment of socio-technical systems is essential to reduce the probability of human error (Cacciabue, 2004).

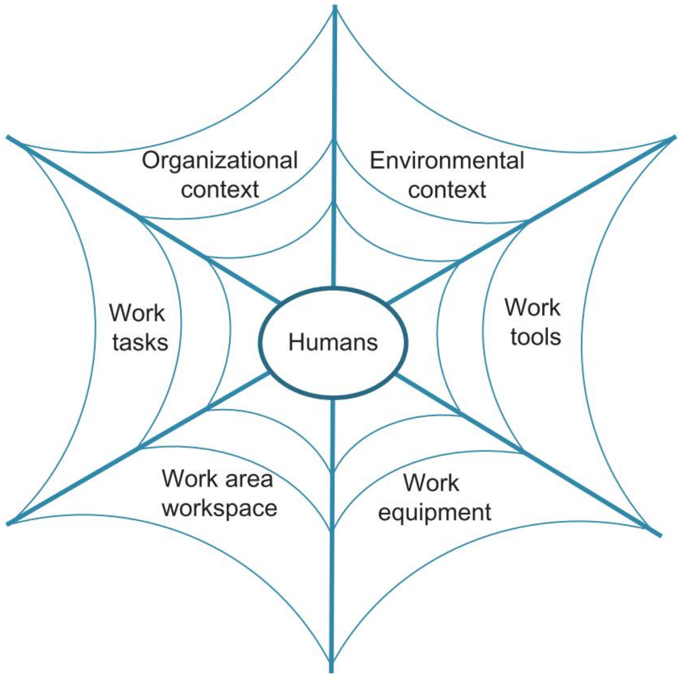

Figure 3.1: Human Factor within the workplace Edmonds (2016)

Furthermore, to eliminate or reduce the impact of the human factor, it is essential to understand the human error mechanism (Aksorn and Hadikusumo, 2007b). Significant efforts to understand human error mechanisms have been carried out and human error models have been developed by experts. Rasmussen (1983) was the pioneer to work on human error mechanisms and developed a well-known model called Skills. Rules, Knowledge (SRK) model to describe the human error. The presented model classifies the errors under skills, rules or knowledge-based performance to understand the occurrence of errors. Skill-based performance required the completion of well-practised action in a familiar environment. These actions involve little or no consciousness, as a result, making the workers overconfident or overfamiliar with the task and surroundings that increasing the chances of error (Scaife and Mitchell, 2016). These kinds of errors include slips, laps or mistakes. Figure 3.2 below shows the (Rasmussen, 1983) skill-rule and knowledge model (SRK).

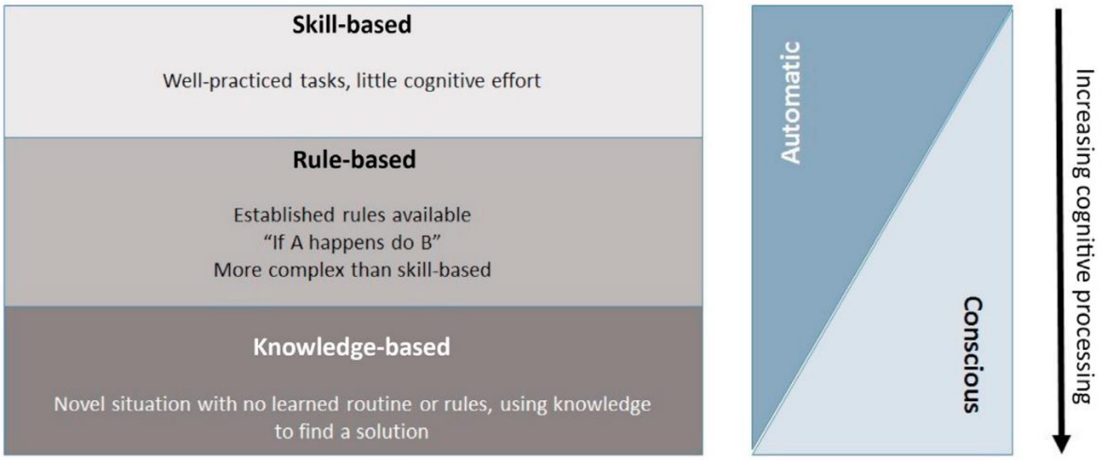

Figure 3.2: Skill, Rule, Knowledge (SRK) Model (Rasmussen, 1983)

Based on the SRK model, Reason (1990) presented its well-known human error model describing the involvement of human factors in the accident mechanism. Reason (1990) categorized human unsafe actions as errors and violations. Errors could be skill-based, rule-based or knowledge-based as proposed by (Rasmussen, 1983), however, Reason (1990) described violations as intended mistakes shown in Figure 3.3. There are also other human error models, however, human error studies established that most unsafe acts are the result of violations (Aksorn and Hadikusumo, 2007b; Hosseinian and Torghabeh, 2012; HSE, 2012; Oswald, Smith and Sherratt, 2015).

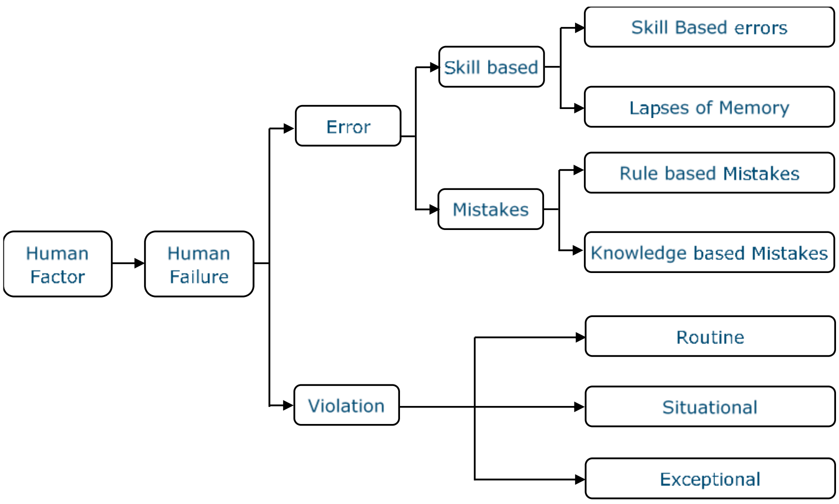

Figure 3.3: Human Error Model (Reason. 1990)

A significant number of researchers have pursued their research in identifying the patterns of human errors to overcome the undesirable impacts of human error in the workplace. For instance, one type of human error is an unintentional failure committed by the person working in a workplace. These types of mistakes or errors are not deliberately done, however, they arose because of an error of judgement (Scaife and Mitchell, 2016). Similarly, since the developments in the field of psychology, the study of human error and error mechanism has been carried out by researchers and human error models to understand error have been developed. Some of the renowned authors who presented human error models are (Reason, 1990b; Wickens, 2000; Boring, 2012). Most of these models identify different types of human error and explain how the error could occur in the workplace and also mention the measures to reduce the likelihood of error. Moreover, with the further advancement in the field, several researchers have also identified the specific conditions which enhance the likelihood of human error by developing accident causation models (Williams, 1986; B. Kirwan, 1994). A detailed review of accident causation models has been carried out in the next section.

3.2.1. Accident Causation Models

Human error cannot be eliminated from any workplace or system as a human makes an error and they always will. However, leaving the error unattended could end up with serious consequences. Prolific research has been carried out and "Accident causation Models" have been developed to study the human error and error mechanism that causes an accident in workplaces. Accident causation models aim to identify the causal factors and processes involved in the accidents to develop plans for accident prevention (Mitropoulos, Abdelhamid and Howell, 2005a). This is the retrospective approach of learning from past incidents to avoid them in future projects (Grant *et al.*, 2018). Ranasinghe et al. (2014) defined the accident causation model as a systematic way of finding the causes of accidents. Accident causation models were originally developed as an occupational accident investigation tool to prevent the repetition of accidents. The ontology of the human factor as a cause of the accident in accident causation models can be traced back to the 1930s, since the evolution of the first accident causation theory. In 1931, H.W. Heinrich being a pioneer in accident investigation, presented a theorem known as 'domino theory' that highlighted the human factor by stating that human unsafe actions and unsafe conditions cause most of the accidents and eventually injuries at the site (Heinrich, 1969).

Following H.W. Heinrich, several researchers after investigating the accidents put forth accident causation theories and models for accident prevention (Fu *et al.*, 2020). Peterson (1971) introduced the "Multiple Causation Theory" which postulates unsafe acts and unsafe conditions behind accident causation (Othman *et al.*, 2018). Bird and Germain 1974 presented a modified domino theory called Bird's accident theory on accident causation emphasizing management as the root cause of accidents that initiates human error and unsafe acts (Bird, 1974; Li and Poon, 2010). The Reason (1974) is also very well-known in safety science for his contribution to accident causation study after H.W. Heinrich. Reason (1977) came forth with the Swiss-Cheese model and presented a systematic approach to deal with latent failures (distal factors) along with root cause investigation (Reason, 2008). Reason (1977) described latent failures as organisational barriers/defence lines against risks and hazards to prevent accidents, these barriers are sequential and for an incident to happen there must be errors across all the defence lines which is a rear case (Larouzee and Le Coze, 2020).

The aforementioned accident causation models served exceptionally well to investigate the root causes or the latent failures in the past, however, recent accident causation models envisaged a system approach to deal with the failures rather than sequential ACM (Haslam *et al.*, 2005; Mitropoulos, Abdelhamid and Howell, 2005a; Grant *et al.*, 2018). (Waterson *et al.*, 2015) demonstrated historical developments in the accident causation models since the 1930s. He categorized accident causation models into Technological, Ergonomics and Complex socio-technical system eras in his timeline shown in Figure 3.4. Woolley et al. (2019) classified accident causation models into 'simple linear models', 'complex linear models, and 'complex non-linear models' based on the error identification approach. 'Simple linear models' also called 'First-generation models' in literature showcase the early accident causation models that dealt with root causes analysis (Hale *et al.*, 2012a; Wang, Zou and Li, 2016; Grant *et al.*, 2018; Harvey, Waterson and Dainty, 2019a; Woolley *et al.*, 2019). 'Complex linear models' or 'Second-generation models' incorporated human factors or ergonomics to mitigate active as well as latent failures (Hale *et al.*, 2012a; Wang, Zou and Li, 2016; Grant *et al.*, 2018; Harvey, Waterson and Dainty, 2019a; Woolley *et al.*, 2019). However, technological advancement in the industry envisaged the researchers to adopt a systemic approach to dealing with accidents (Haslam *et al.*, 2005; Mitropoulos, Abdelhamid and Howell, 2005a).

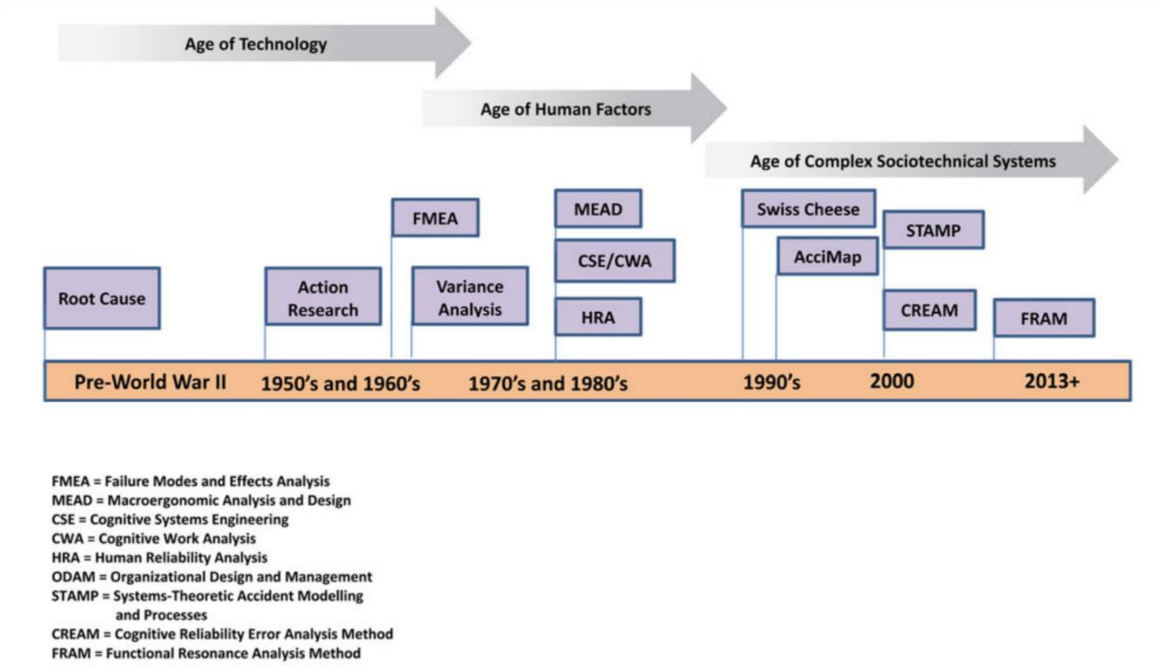

Figure 3.4: Historical Development Of Accident Causation Model (Waterson et al., 2015)

Subsequently, researchers in recent decades opted to adopt a systematic approach to deal with inevitable accidents in complex dynamic systems (Haslam *et al.*, 2005; Katsakiori, Sakellaropoulos and Manatakis, 2009; Hosseinian and Torghabeh, 2012; Grant *et al.*, 2018;

Woolley *et al.*, 2019). Hence, recent accident causation models focused on a systematic approach to dealing with factors causing accidents in complex socio-technical systems (Nawi *et al.*, 2016; Harvey, Waterson and Dainty, 2019b; Woolley *et al.*, 2019; Dhalmahapatra, Das and Maiti, 2020). Rasmussen (1997) pioneered the concept of a systemic approach to deal with inevitable accidents rather than eliminating the root causes and latent failures. Rasmussen (1997) argued for top-bottom systematic safety management incorporating the government and the regulatory bodies above the organisational level shown in Figure 14. He presented a Risk Management Framework (RFM) to elaborate on the risk associated at each organisational level (i.e. government, regulator, organisation, management, staff and work). Of many ACM based on the system approach developed by the researchers, RFM is the most famous and cited framework. System ACMs consider the complex relationship between safety factors at different organisational levels as the causes of accidents (Woolley *et al.*, 2019). Furthermore, a traditional system approach is based on the core principle that safety is the collective responsibility of everyone’s actions and decisions in the system and contributing factors couldn’t necessarily be individual errors or violations, however, emerge from the dynamic and complex interaction between contributing factors and associated actor throughout the entire system (Rasmussen, 1997; Leveson, 2004; Haslam *et al.*, 2005; Salmon *et al.*, 2017).

3.2.1.1. The Domino Theory

In 1931, H.W. Heinrich being a pioneer in accident investigation, presented a theorem known as ‘domino theory’ and highlighted the human factor by stating that human unsafe actions and unsafe conditions cause most of the accidents and eventually injuries at the site (Heinrich *et al.*, 1980). The ‘Domino’s Theory’ presented by (Heinrich *et al.*, 1980) stated that the occurrence of occupational injury at the workplace is the result of a sequence of complicated factors and the last of which is accident itself. This theory first listed the chain of events in chronological order that leads to the occurrence of an injury. Furthermore, Heinrich et al.

(1980) mentioned that five dominos are standing in a sequence one after the other which leads to the injury so that when one domino falls it knocks down the next domino itself which initiates the fall of all dominos. The sequence is listed as:

Injury by an;

accident, due to;

Unsafe act of a person, due to;

The fault of the person is caused by;

Ancestry and social environment.

It further noted that to prevent an injury to happen it is essential to remove any one of the dominos to break the sequence of falls. Figure 3.5 below explains the domino effect described in the domino theory.

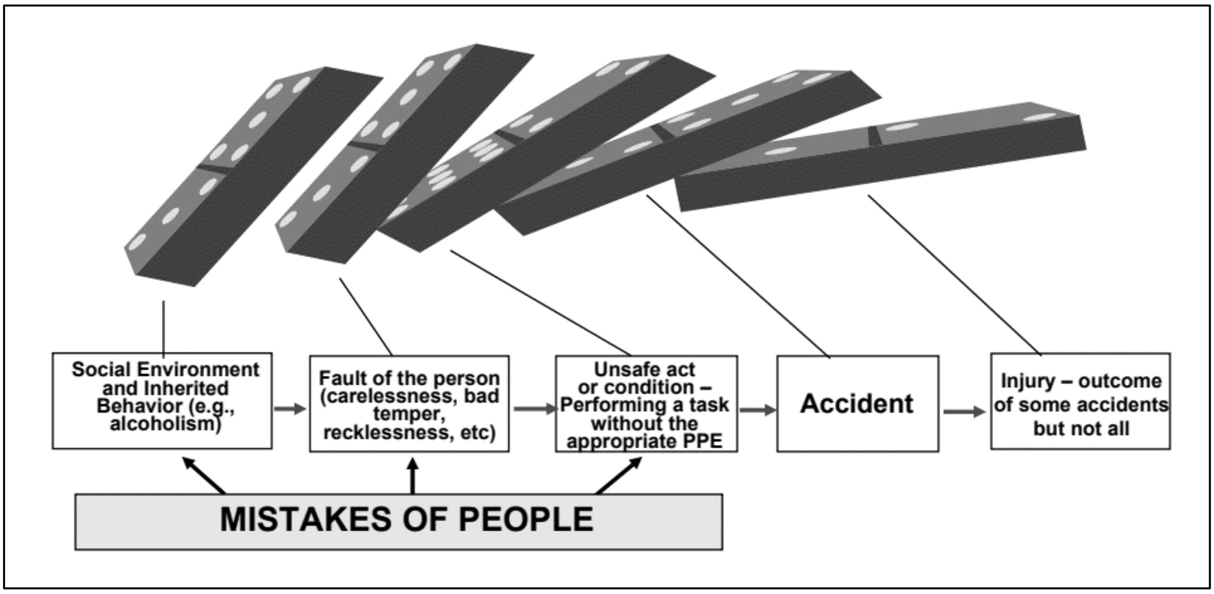

Figure 3.5: Heinrich's Dominos Theory (Heinrich et al., *1980)*

The different stages of the domino’s theory are described below;

a) Ancestry or Social Environment: The ancestry or the social environment describes the impact of inherited personal behaviour as well as the workplace surroundings on the worker's skills, and perception of safety (Saxena, 2017).

b) The Fault of the Person: This describes the impact of human factors to enter an unsafe situation or commit the potential fault or mistake which leads to the accident on site. People have tendencies to get into unsafe conditions either intentionally or intentionally (Reason, 1990b).

c) The Unsafe Act: Unsafe act represents an act that causes harm or injury. This could be the fault of the person working on the site which leads to the accident.

d) Accident: This domino represents the accident caused by the fall of antecedent dominos.

e) Injury Itself: This represents the injury to the worker on site. The domino accident model advocates the unidimensional sequence of events caused by multiple factors.

3.2.1.2. Bird's Model of Accident Causation

Bird and Loftus (1976) presented a modified "Domino's Theory" taking into account the role of management in the sequence of events defined by Heinrich (Domino Theory). They further added basic causes (personal and job factors|), immediate causes (standard practices, conditions) that lead to the incident and eventually personal or property loss. This updated version of the "Domino Theory" is known as the Bird Model of accident causation. Bird's Model of accident causation can be applied to all types of accident investigations (Hosseinian and Torghabeh, 2012). The sequence of events involved in the Bird Model are;

a) Lack of Control/Management: Caused by inadequate program, Inadequate program standards, and inadequate compliance to the standard.

b) Basic Causes: Due to personal or job factors.

c) Immediate Causes: Caused by sub-standard practices and conditions.

d) Incident: Due to contact with energy or substance.

e) Loss: Loss to the people or property.

Figure 3.6 below shows the sequence of events involved in the Birds Model.

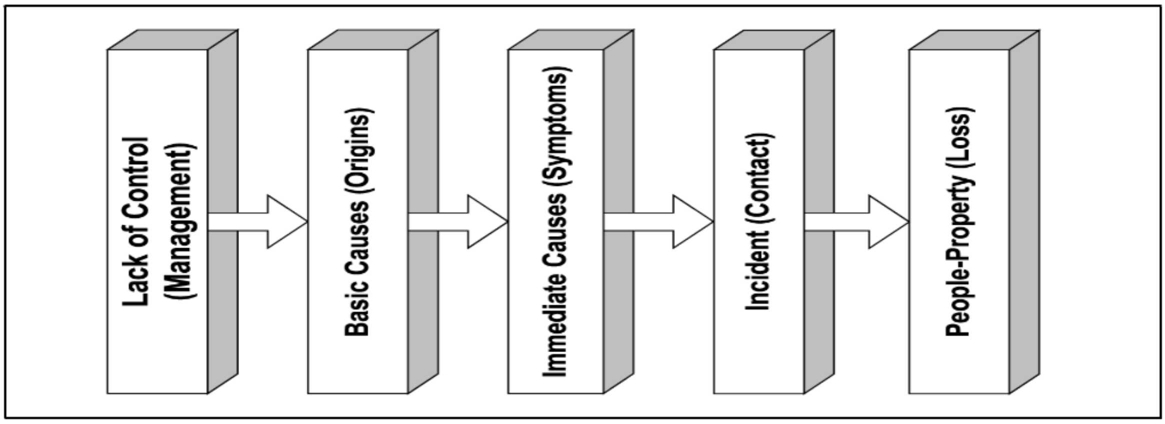

Figure 3.6: Birds Model of Accident Causation (Bird and Loftus, 1976)

3.2.1.3. The Swiss Cheese Model

Reason (1990b) presented the Swiss Cheese Model as an accident causation model to explain the occurrence of incidents at the workplace. This model drew the attention of health and safety professionals to eliminate accidents by introducing defences. This method explains that to avoid the occurrence of an accident the organisation must introduce several additional barriers to stop the risks and hazards that become accidents (Reason, 1990b). Reason (1990) further explains that although organisations have barriers in place to prevent accidents to happen, however, these barriers have holes in them like slices of Swiss Cheese which he called defects in the barriers shown in Figure 3.7.

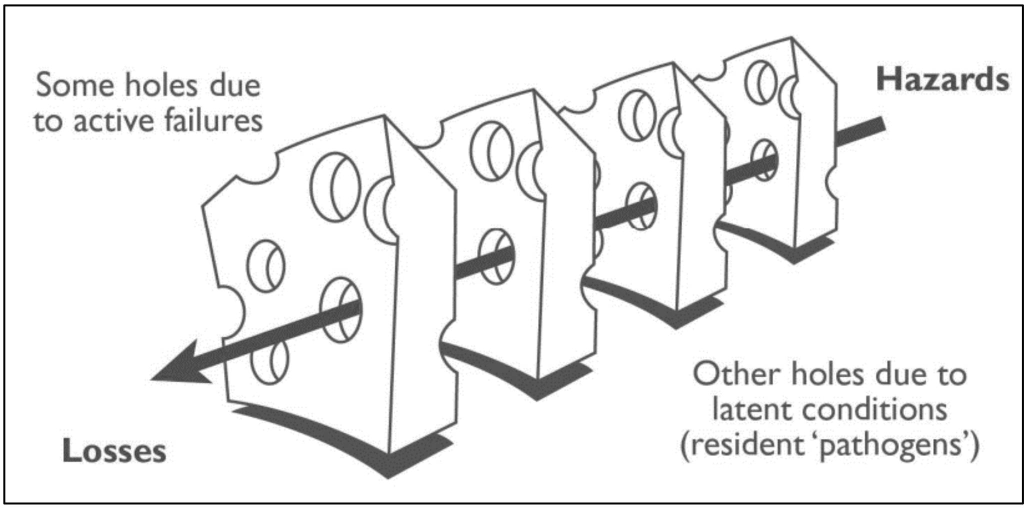

Figure 3.7: Organisational Barriers to Prevent Accidents (Reason, 1990)

Reason (1977) stated that organisations have barriers/defence lines against risks and hazards to prevent accidents, these barriers are sequential and for an incident to happen there must be human errors across all the defence lines which is a rear case (Larouzee and Le Coze, 2020). When these holes or defects come across then accident is certain to happen, however, the introduction of additional barriers could help to prevent the accidents. Moreover, Reasons (1990) introduced the active or latent failures in the Swiss Cheese Model to explain the occurrence of failure. Figure 3.8 elaborates on the barriers presented in the Swiss Cheese Model. Reason (1990) believes that holes are an unsafe act because of human error which represents active failure, and most accidents are the cause of active failure which is the result of mistakes, violations, or slips. Reason (1990b) further divided the barriers/defences into two groups as described below;

a) Soft Barriers: According to Reason (1990) these are the organisational barriers or defences which are dependent on the safety procedures or the safety personnel. Soft barriers involve the supervisors, operators, and safety regulations that have defects that cause accidents in the workplace.

b) Hard Barriers: Hard barriers are the additional barriers proposed by Reason (1990) that includes automatic warning systems, physical obstacles or safety devices that prevent accident in case of failure of soft barriers.

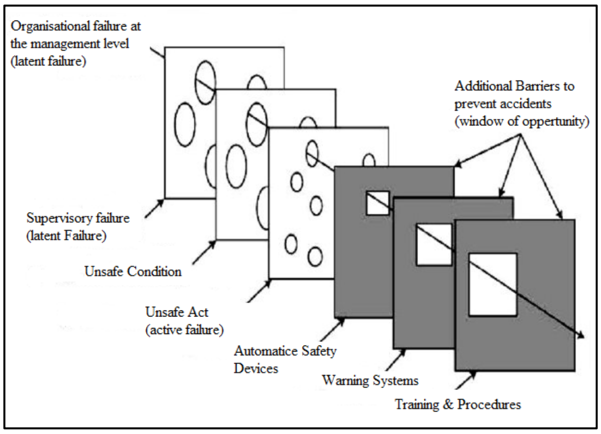

Figure 3.8: Reason's Swiss Cheese Model (Reason, 1990)

3.2.2. Accident Causation Models in Construction Industry

Accident causation also prevailed in the construction industry based on the accidents studied by the researchers. For instance, McClay (1989) presented the "Universal Framework" for accident causation in construction and identified hazards, human unsafe actions and functional limitations as major causes of accidents. Hinze (1997) known for his contribution to accident causation in the construction industry, came up with a "Distraction Theory" stating that distraction from hazards due to work pressure increases the probability of accidents on construction sites. Furthermore, Haslam et al. (2003) developed a systematic accident causation framework called the ConAC Framework based on the analysis of 100 minor construction accidents. ConAC Framework characterised the causal factors into 'originating factors', 'shaping factors' and 'immediate factors' shown in Figure-4. Manu et al. (2010) linked accident causation with construction project features and the proximal factors shown in Figure 3.9.

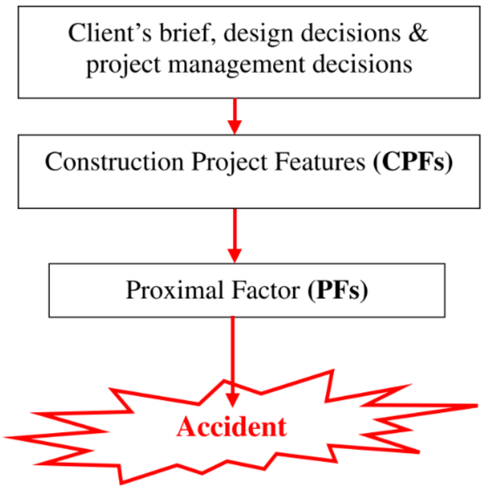

Figure 3.9: Accident Causation Based on CPFs (Manu et al.*, 2010)*

Contemporary researchers in the construction industry have studied accidents in the construction industry to find out the root causes of accidents (Shappell and Wiegmann, 1997; Manu, 2013; Mohammadi, Tavakolan and Khosravi, 2018b). Human unsafe behaviour and actions are consistently found as major causes of accidents in the construction industry (Hosseinian and Torghabeh, 2012). Winge, Albrechtsen and Mostue (2019) investigated hundred and seventy-six construction accidents and ranked worker action as the top and most catastrophic factor causing most of the accidents in construction. Referring to these studies, human error quite predominantly represents a major cause of accidents in the construction industry. The past two decades of research exhibit well the pertaining factors causing accidents in the construction industry, however, the contemporary research revealing the human factors as accident causation factors confirms that no improvement has been made in the past twenty years (Nawi *et al.*, 2016; Zahoor *et al.*, 2017; Franciosi *et al.*, 2019; Winge, Albrechtsen and Mostue, 2019; Khalid, Sagoo and Benachir, 2021).

Henceforth, accident causation models contributed substantially to the construction industry in identifying the proximal, latent and influencing factors, however, these retrospective models offer no help in managing these factors (Jenkins *et al.*, 2010; Apostol-mates and Barbu, 2016). For instance, ConAC Framework systematically channelizes the factors into immediate, shaping and originating factors but is untalkative on how to and at what organisational level these factors can be eliminated (Gibb *et al.*, 2014). Furthermore, applying the ACM model for root cause analysis is not the question anymore, rather investigations should be carried out on finding the contributing factors and finding out their relationships at different levels in the complex socio-technical construction system (Woolley *et al.*, 2019). Construction being one of the complex dynamic socio-technical industries entails a high risk of accidents due to the involvement of human actions throughout the project execution (Hovden, Albrechtsen and Herrera, 2010; Oswald, Smith and Sherratt, 2015). Therefore, to deal with the complex dynamic socio-technical impact on safety, it is indispensable to develop more resilient approaches or frameworks to manage safety (Hovden, Albrechtsen and Herrera, 2010). The research, therefore, aimed to conduct empirical research targeting to explore the H&S professional's perception of the UK construction industry on accident causation and elimination of human error.

3.2.3. Human Reliability Analysis (HRA)

HRA is one of the most frequently used systematic techniques to identify, quantify and mitigate human error in complex safety systems (Hou *et al.*, 2021). HSE defined human reliability assessment as a quantitative or qualitative method to assess the contribution of humans to the error (HSE, 2009). Similarly, Kirwan (1998) stated that HRA methods are the probabilistic risk assessment and cognition modelling to mitigate human error. Furthermore, Human reliability assessment (HRA) is a method for probabilistic qualitative and quantitative assessment of human errors in a human-technical system (Calixto, 2016; Hou *et al.*, 2021). Reason (1990a) stated that human error usually occurs when physical and cognitive abilities are overwhelmed by environmental demands. Subsequently, quantifying human error could be a complicated and troublesome task to carry out in any industry; even the experts could be prone to errors due to the wrong comprehension of the situation (Davis, 1982). However, probabilistic risk assessment is essential to evaluate and analyse the possible accident scenarios for safety-critical activities in a complex system. Human reliability analysis (HRA) has been successfully used in safety-critical industries especially nuclear and other complex socio-technical industries to reduce the likelihood of human error (Ung, 2015). However, in the construction industry, no standard procedures or guidelines have been introduced to minimize the probability of human error in hazardous activities (Kazmi *et al.*, 2016). Subsequently, the practice of HRA started around the 1950s with the technological advancement in the industries, however, the first formal HRA method was presented in a symposium meeting of safety experts in the 1960s (Swain, 1990; Karwowski, 2006; Boring, 2012).

The pioneering HRA method introduced was the "Technique for Human Reliability Error Rate Prediction (THERP)" to model human reliability for the nuclear industry in response to the tragic nuclear accident at Three Mile Island (Nazin and Fass, 2015). Since then, there has been a proliferation of HRA methods by researchers for different industries to quantify human reliability under complex situations (Boring, 2012). Generally, an HRA method involves the quantification of human error probability (HEP) for a system or task against performance shaping factors (PSF) (Kirwan, 1997; Bai and Jin, 2016; Emstsen, Nazir and Roed, 2017). Performance shaping factors (PSF) are the contributing factors that may influence human performance in an HRA (Park, Jung and Kim, 2020). A significant study to explore the contributing factors has been conducted by the researcher in the past few years (Jannadi, 1996; Hale *et al.*, 2012b; Mohammadi, Tavakolan and Khosravi, 2018b). Furthermore, PSFs have been categorized into three classes; External, Internal and physiological factors (Abbassi *et al.*, 2015). External factors are defined by the characteristics of the work environment, equipment, situation, task and procedural instructions. The internal factors are associated with personal characteristics such as skills, experience, mental health and motivation etc. However, psychological and physiological factors; also called stressors; are the factors that directly affect mental stress or physical stress such as workload, work speed, and working in extreme conditions (Groth and Mosleh, 2012; Yang, Tao and Bai, 2014; Abbassi *et al.*, 2015; Calixto, 2016; Franciosi *et al.*, 2019). A list of commonly proposed PSFs is given in Table 3.1.

Table 3.1: Performance Shaping Factors (PSFs)

Performance Shaping Factors (PSF) / Performance Influencing Factors (PIF)		
Job Factors	**Personal Factors**	**Organisational Factors**
Instructions	Competence	Peer Pressure
Equipment / Tools	Motivation	Communication
Communication	Fatigue	Safety Culture
Procedure / Design	Stress / Morale	Roles & responsibilities
Complexity / Difficulty	Commitment	Workload
Time	Workload	Management
Environment	Communication	Supervision

Furthermore, a traditional HRA has been carried out in three distinct phases; (i) modelling of potential human error, (ii) identification of potential human error after applying the PSFs, and

(iii) quantification of human error (Swain and Guttmann, 1982; Mosleh *et al.*, 2010). Additionally, HRA methods are based on two core principles for human error assessment; (i) expert opinion and (ii) human error database (Abbassi *et al.*, 2015). The expert opinion technique involves acquiring expert judgements from several experts having complete knowledge about the task for which HEP is assessed. The analyst review the relevant PSFs against the task and opinions are provided which are used to calculate the overall HEP value using an appropriate HRA method (Boring, Griffith and Joe, 2007). Boring, Griffith and Joe (2007) further stated that analysts may review a possible list of PSFs to identify human error. The most common methods in this category are; the Success likelihood index method (SLIM) and Absolute Probability Judgement (APJ) methods. On the other hand, the human error database techniques encompass the dataset of human error probabilities to be used within the framework of the specific HRA method to obtain the HEP value (Pouya and Habibi, 2015). The common HRA methods which use human error database are; Human Error Reduction Technique (HEART), the Technique for Human Error-Rate Prediction (THERP) and (JEIDI) (HSE, 2009; Bolt *et al.*, 2010; Fan *et al.*, 2020). Below are two methods that can be used in the construction industry for human error assessment.

3.2.3.1. Technique for Human Error-Rate Prediction (THERP)

THERP is a pioneering technique in HRA and still is the most widely used approach in several industries for human error assessment (Yang, Tao and Bai, 2014). THERP was introduced as a formal HRA method in 1663 in a health and safety meeting by Dr Alan Swain. At first, THERP was applied only to the nuclear industry however, subsequently, the later versions of this technique became a guideline for plant safety assurance (Swain and Guttmann, 1982). This technique uses an error probabilities database developed by safety analysts which quantifies HEPs for the task using PSFs (Kazmi *et al.*, 2016). Furthermore, to analyse the error probabilities, this methodology decomposes the task into sub-tasks to select the possible error data from the THERP HEP handbook (Abbassi *et al.*, 2015). In the later step, the relationship between different HEPs is considered and the final HEP is calculated using the human reliability tree (Calixto, 2016). The steps involved to perform THERP are shown in Figure 3.10.

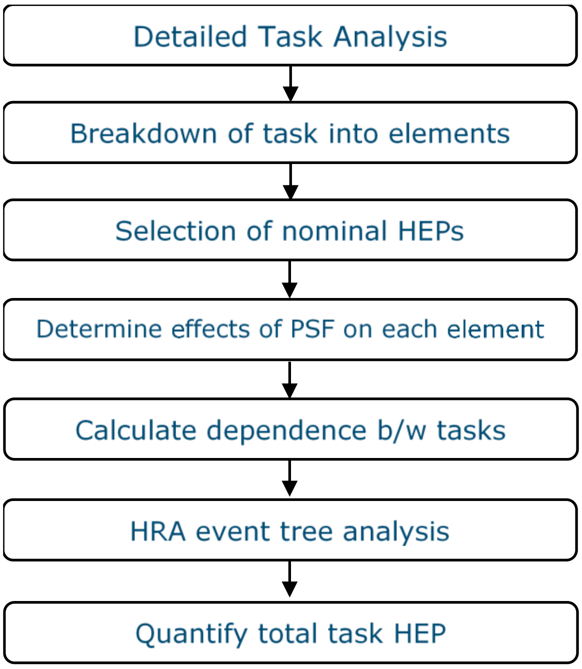

Figure 3.10: THERP Analysis Technique (Swain and Guttmann, 1982)

3.2.3.2. Cognitive Reliability and Error Analysis Method (CREAM)

The cognitive Reliability and Error Analysis Method (CREAM) is a second-generation HRA method developed by Erik Hollnagel in 1998 considering the short-coming of the first-generation methods (HSE, 2009). CREAM has been introduced to deal with more sophisticated industrial processes with high unpredictability of human error (Pouya and Habibi, 2015). This HRA method is developed to assess as well as evaluate the human error probabilities based on human cognition and the surrounding situation. Furthermore, this method allows the retrospective analysis of past events as well as the prospective human error analysis to predict how the error could potentially occur (Felice *et al.*, 2013). The CREAM method starts with the analysis of a task or situation using Common Performance Conditions (CPCs) followed by the context description of the action and cognitive activities to perform error predictions. Finally, quantification of likely human error is conducted to evaluate the error probabilities (Hollnagel, 1998). The steps involved in the CREAM model are shown in Figure 3.11 below.

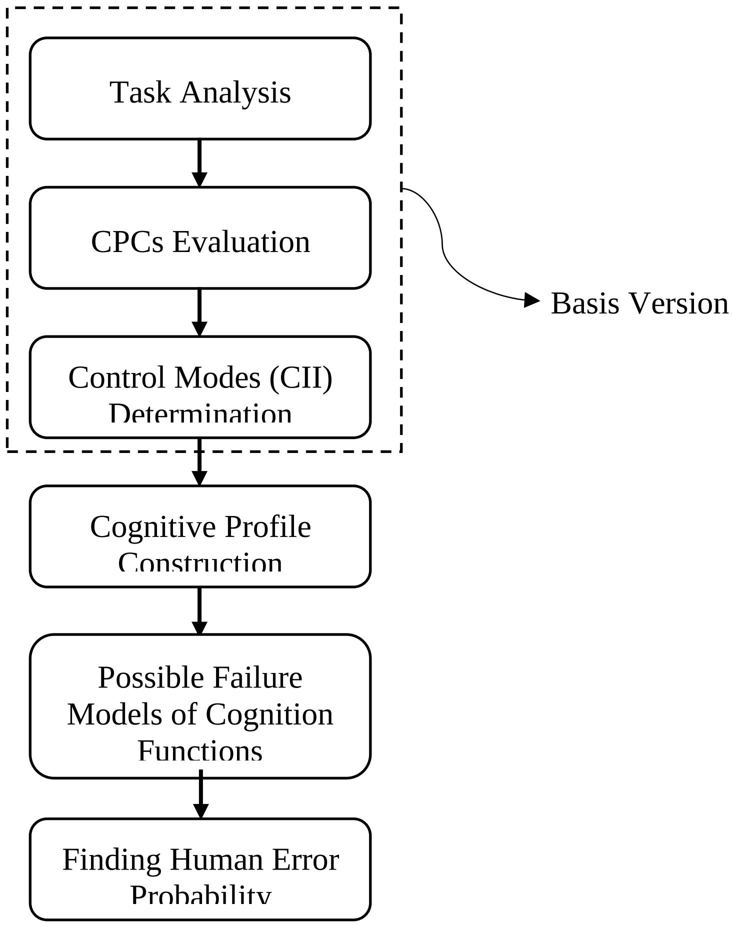

Figure 3.11: Steps involved in the CREAM Model (Hollnagel, 1998)

The basic version of the CREAM model consists of a qualitative classification of CPCs only but doesn't include a quantification process (Capt. Sameh Kabary Rashed, 2016). However, the extended version allows the analyst to determine the task which requires human cognition and also it is capable to identify the conditions where cognitive reliability is reduced enhancing the risk at the workplace (Ung, 2015). CREAM is a retrospective tool to analyse the historical occurrence of an error as well as a prospective analysis tool to assess error probability in the high-risk task. The introduction of Common Performance Conditions (CPCs) to identify the error conditions was a new concept proposed in this Model. CPCs were developed to identify the condition of likely performance. A detailed review of CPCs has been provided in the next section.

3.2.3.2.1. Common Performance Conditions (CPCs)

Hollnagel (1998) in his model listed nine factors that affect human reliability in a system called Common Performance Condition (CPCs) which are listed as follow; (i) adequacy of organisation, (ii) working conditions, (iii) adequacy of man-machine interface, (iv) availability of plans and procedures availability, (v) time availability (vi) number of simultaneous goals, (vii) time of day, (viii) adequacy of training and experience and (ix) quality of crew collaboration. The first step in this model is to apply the task steps to the CPCs in Table 3.2 below. This step involves an expert's judgement to obtain the level of CPCs of certain task steps. Based on the CPCs the probabilities of human cognition and actions to perform an error are measured on a scale of four characteristics called Control Modes namely; “Scrambled”, “Opportunistic”, “Tactical”, and “Strategic” shown in Figure 3.12. The assessor uses Table 3.3 to find the scores of each CPCs for a task on a scale of three; ∑reduced, ∑not significant, and ∑improved reliability ((Hollnagel, 1998). The CII is represented by the formula below.

$$\text{CII} = \sum\text{reduced} - \sum\text{improved}$$

And

$$\text{CII} = \sum_{i-1}^{9} PII$$

Whereas;

CII = context influence index)

PII = Performance Influence Index

The value of CII represents the control mode using Figure 3.12. If the value of CII is not significant then it can be ignored as it indicates minor or no effect on human reliability.

Table 3.2: CPCs and Performance Reliability (Hollnagel, 1998)

CPCs	CPC Levels/Descriptors	Expected Effects on Performance Reliability	Performance Influence Index PII
Adequacy of Organisation	Very Efficient Efficient Inefficient Deficient	Improved Not Significant Reduced Reduced	-0.6 0 0.6 1.0
Working Conditions	Advantageous Compatible Incompatible	Improved Not Significant Reduced	-0.6 0 1.0
Adequacy of human-machine interaction and operational support	Supportive Adequate Tolerable Inappropriate	Improved Not Significant Not Significant Reduced	-1.2 -0.4 0 1.4
Availability of procedures/plans	Appropriate Acceptable Inappropriate	Improved Not Significant Reduced	-1.2 0 1.4
Number of Simultaneous goals	Fewer than capacity Matching current capacity More than capacity	Not Significant Not Significant Reduced	-1.2 0 1.4
Available time	Adequate Temporary inadequate Continuously inadequate	Improved Not Significant Reduced	-1.4 0 2.4
Time of delay when the task is performed	Daytime (adjusted) Nighttime (unadjusted)	Not significant Reduced	0 0.6
Adequacy of training and preparation	Adequate high experience Adequate low experience Inadequate	Improved Not significant Reduced	-1.4 0 1.8
Crew collaboration quality	Very Efficient Efficient Inefficient Deficient	Improved Not significant Not Significant Reduced	-1.4 0 0.4 1.4

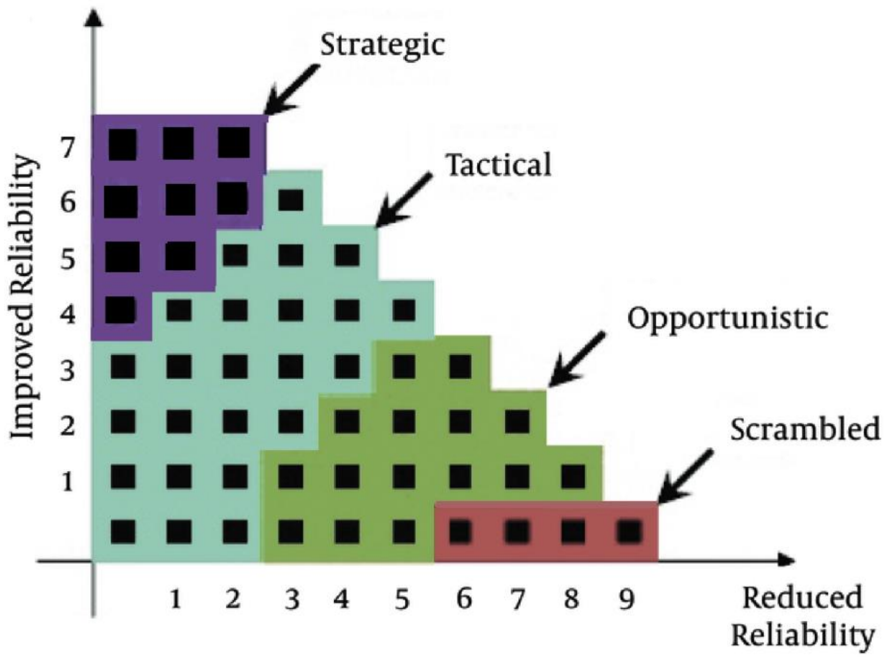

Figure 3.12: CPCs scores and Control Modes (Hollnagel, 1998)

Table 3.3: CREAM Control Modes (Hollnagel, 1998)

Control Modes	**HEP Interval**	**CII Value**	**Control Modes Descriptor**
Strategic	0.0005 < HEP < 0.01	-7 to -3	Adequate time, management and organisational support, practical, assessable to consider the action.
Tactical	0.001 < HEP < 0.1	-3 to 1	The performance follows planned procedures
Opportunistic	0.01 < HEP < 0.5	2 to 5	Condition is characterised by a lack of planning
Scrambled	0.1 < HEP < 1.0	6 to 9	The next action is disorganised or unexpected

3.2.3.3. Human Error Assessment and Reduction Technique (HEART)

The Human Reliability Assessment and Reduction Technique (HEART) is another Human reliability assessment tool to analyse the risk and probability of error in human performance in a systematic way (Bell and Williams, 2018). Williams (1986) proposed this technique of human error assessment and error reduction. This method works based on the fact that for any task to be carried out there is a probability of error/failure. These tasks (Williams, 1986) mentioned the varying level of Error Producing Conditions (EPCs) that can influence human reliability in a workplace. Furthermore, this method allows the assessor to modify the human reliability data specific to the risks involved in the task (Kazmi *et al.*, 2016). Additionally, Bell and Williams (2018) argued that this method is comparatively quick, and straightforward and can be appropriate for any industry where human reliability is considered important.

The HEART method introduced 38 error-producing conditions (EPCs) related to the focused task instead of Performance Shaping Factors (PSFs) used in the other HRA methods shown in Table 3.6 below (Kazmi *et al.*, 2016). Most of the EPCs are common in use such as time, unfamiliarity, inadequate procedures and poor feedback etc. The calculation of HEART is carried out in five steps; task selection, assigning nominal HEP, identifying EPCs, combining the proportion of each EPC on nominal HEP, and lastly, basic HEP calculation as shown in Table 3.4 below (Williams, 1986). Hence, HEART calculation is dependent on Generic Error Probability (GEP) and related EPCs. Generic Error Probability (GEP) must be selected from given criteria A-H relevant to the EPCs as shown in Table 3.5. Eventually, human error probability (HEP) is calculated as shown in Figure 3.13 below.

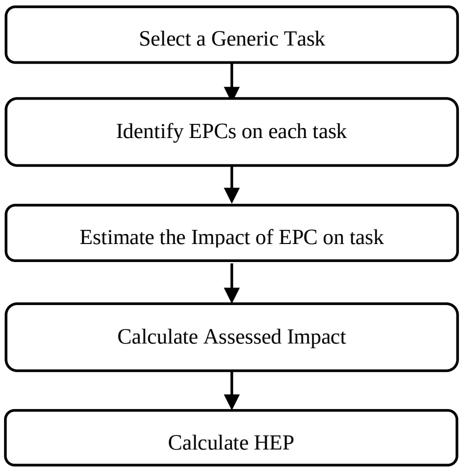

Figure 3.13: HEART Methodology (Bell and Williams, 2018)

Table 3.4: HEART Calculation (Bell and Williams, 2018)

Step	Task	Output
1	Generic Task Unreliability: Classify the task into one of the 8 (A-H) generic task types (Table 14)	Nominal human unreliability
2	Error Producing Condition & Multiplier: Identify relevant EPCs to the task under analysis (Table 15).	Maximum predicted nominal HEP which may increase unreliability (Multiplier)
3	Assessed Proportion of Effect: Estimate the impact of each error-producing condition (EPCs) on the task under analysis based on judgment	(Assessed Proportion of effect) between 0 and 1
4	Assessed Impact: Calculate the assessed impact of each EPC by the formula: ((Multiplier-1) Assessed Proportion of effect)+1	Assessed impact value
5	Human Error Probability: calculate overall HEP using the formula Nominal human unreliability X Assessed impact1 X Assessed Impact 2….. etc	Overall Error Probability

Table 3.5: Generic Task Unreliability (Williams, 1986)

Generic Task Unreliability

Generic task		*Proposed nominal human unreliability (5th–95th percentile boundaries)*
A	Totally unfamiliar, performed at speed with no real idea of likely consequences	0.55 (0.35–0.97)
B	Shift or restore system to a new or original state on a single attempt without supervision or procedures	0.26 (0.14–0.42)
C	Complex task requiring high level of comprehension and skill	0.16 (0.12–0.28)
D	Fairly simple task performed rapidly or given scant attention	0.09 (0.06–0.13)
E	Routine, highly practised, rapid task involving relatively low level of skill	0.02 (0.007–0.045)
F	Restore or shift a system to original or new state following procedures, with some checking	0.003 (0.0008–0.007)
G	Completely familiar, well-designed, highly practised, routine task occurring several times per hour, performed to highest possible standards by highly motivated, highly trained and experienced person, totally aware of implications of failure, with time to correct potential error, but without the benefit of significant job aids	0.0004 (0.00008–0.009)
H	Respond correctly to system command even when there is an augmented or automated supervisory system providing accurate interpretation of system stage	0.00002 (0.000006–0.00009)
M	Miscellaneous task for which no description can be found. (Nominal 5th to 95th percentile data spreads were chosen on the basis of experience suggesting log-normality)	0.03 (0.008–0.11)

Table 3.6: Error Producing Conditions (EPCs) (Williams, 1986)

Error-Producing Conditions (EPCs)

	Error-producing condition	*Maximum predicted nominal amount by which unreliability might change going from 'good' conditions to 'bad'*
1.	Unfamiliarity with a situation which is potentially important but which only occurs infrequently or which is novel	× 17
2.	A shortage of time available for error detection and correction	× 11
3.	A low signal-to-noise ratio	× 10
4.	A means of suppressing or overriding information or features which is too easily accessible	× 9
5.	No means of conveying spatial and functional information to operators in a form which they can readily assimilate	× 8
6.	A mismatch between an operator's model of the world and that imagined by the designer	× 8
7.	No obvious means of reversing an unintended action	× 8
8.	A channel capacity overload, particularly one caused by simultaneous presentation of non-redundant information	× 6
9.	A need to unlearn a technique and apply one which requires the application of an opposing philosophy	× 6
10.	The need to transfer specific knowledge from task to task without loss	× 5.5
11.	Ambiguity in the required performance standards	× 5
12.	A mismatch between perceived and real risk	× 4
13.	Poor, ambiguous or ill-matched system feedback	× 4
14.	No clear direct and timely confirmation of an intended action from the portion of the system over which control is to be exerted	× 3
15.	Operator inexperienced (e.g. a newly qualified tradesman, but not an 'expert')	× 3
16.	An impoverished quality of information conveyed by procedures and person–person interaction	× 3
17.	Little or no independent checking or testing of output	× 3
18.	A conflict between immediate and long-term objectives.	× 2.5
19.	No diversity of information input for veracity checks	× 2.5
20.	A mismatch between the educational achievement level of an individual and the requirements of the task	× 2
21.	An incentive to use other more dangerous procedures	× 2
22.	Little opportunity to exercise mind and body outside the immediate confines of the job	× 1.8
23.	Unreliable instrumentation (enough that it is noticed)	× 1.6
24.	A need for absolute judgements which are beyond the capabilities or experience of an operator	× 1.6
25.	Unclear allocation of function and responsibility	× 1.6
26.	No obvious way to keep track of progress during an activity	× 1.4
27.	A danger that finite physical capabilities will be exceeded	× 1.4
28.	Little or no intrinsic meaning in a task	× 1.4
29.	High-level emotional stress	× 1.3
30.	Evidence of ill-health amongst operatives, especially fever	× 1.2
31.	Low workforce morale	× 1.2
32.	Inconsistency of meaning of displays and procedures	× 1.2
33.	A poor or hostile environment (below 75% of health or life-threatening severity)	× 1.15
34.	Prolonged inactivity or highly repetitious cycling of low mental workload tasks	× 1.1 for first half-hour × 1.05 for each hour thereafter
35.	Disruption of normal work-sleep cycles	× 1.1
36.	Task pacing caused by the intervention of others	× 1.06
37.	Additional team members over and above those necessary to perform task normally and satisfactorily	× 1.03 per additional man
38.	Age of personnel performing perceptual tasks	× 1.02

3.3. Human Reliability Assessment in Construction Industry

Construction being one of the complex industries entails a high risk of accidents due to the involvement of human actions throughout the project execution (Oswald, Smith and Sherratt, 2015). The high accident rates due to human error require more attention; since it is one of the most prominent factors affecting the performance of the construction industry (Larouzee and Le Coze, 2020). Several efforts have been made to eliminate human error from the construction process to avoid accidents (Kariuki and Löwe, 2007; Hale *et al.*, 2012a; Ye *et al.*, 2018; Ramprasad *et al.*, 2019; Milazzo *et al.*, 2021). Accident causation models (described above) contributed substantially to identifying the root cause of accidents, however, these traditional models retrospectively analyse the incidents ignoring the complexity of the system or environment (Jenkins *et al.*, 2010; Apostol-mates and Barbu, 2016). Furthermore, these retrospective models of identifying the error from past incidents use a top-to-bottom safety management approach to eliminating the errors through the organisational system (Moaveni, Banihashemi and Mojtahedi, 2019). Having said that, it is evident from the literature that a proactive human risk assessment approach is required to mitigate human errors in the construction industry (Fargnoli and Lombardi, 2019).

Nevertheless, the HRA approach has successfully been used in several industries to control the personal characteristics and behavioural aspects of the workers in a human-machine system (Ung, 2015). The construction industry which relies heavily on human actions and human reliability in construction activities decides the successful completion of the project (Ramprasad, Kumar and Prabhat Kumar, 2019). In the context of HRA, limited attention has been given to eliminating human error from the construction process using the HRA approach. Moaveni, Banihashemi and Mojtahedi (2019) argued that the use of HRA can help to reduce the probability of human error in the construction industry, however, very limited use of HRA is found in the literature. Priska *et al.* (2020) applied the CREAM method to analyze the worker's behaviour and related risk in Indonesia's construction industry. Many researchers and safety professionals have recommended the use of HRA to reduce the human factor risk (HSE, 2009; Hou *et al.*, 2021), however, only a few have implemented the concept of human reliability in the construction for safe work execution (Fargnoli and Lombardi, 2019; Priska *et al.*, 2020). Several reasons have been found which limit the use of HRA in the construction industry which are discussed in the next section.

3.3.1. Limitations of Human Reliability Analysis for the Construction Industry

Nevertheless, the HRA approach has successfully been used in several industries to control the personal characteristics and behavioural aspects of workers in a complex human-machine system (Ung, 2015). The construction industry which heavily relies upon and is also the victim of human actions has not benefited from HRA methods (Ramprasad *et al.*, 2019). Although technological advancements in the construction industry have helped the construction industry with better risk assessment and safety management, however, human error is still found to have appalling effects on the construction industry. According to the literature, limited attention has been given to eliminating human error from the construction process, however, recommendations have been made by the researchers to use HRA. For instance, Moaveni, Banihashemi and Mojtahedi (2019) reviewed the HRA models and mentioned that HRA could help to reduce the probability of human error in the construction industry. Similarly, Priska Sinabariba et al. (2020) applied the CREAM method to analyse workers' behaviour and related risk in Indonesia’s construction industry. Several researchers and safety professionals have recommended the use of HRA in the construction industry to reduce the human factor risk (HSE, 2009; Hou *et al.*, 2021), however, only a few have implemented the concept of human reliability in construction for safe work execution (Fargnoli and Lombardi, 2019; Priska Sinabariba *et al.*, 2020).

In the construction industry, the traditional way of dealing with any sort of risk associated with the construction process is known as “risk assessment” (Pinto, Nunes and Ribeiro, 2011). However, Aven (2003) argued that risk assessment and reliability analysis are two distinct subjects with a great deal of overlap. Reliability engineering is narrow in scope than risk assessment and tends to deal with engineered systems which demand high reliability and are subjected to repeated failures (Swain, 1990; French *et al.*, 2011). Furthermore, human behaviour is complex and usually non-rational in a complex socio-technical system driven by the number of external and internal factors that leads to the terminologies ‘error’, ‘slip’, and ‘trip’ within HRA (Hou *et al.*, 2021). Moreover, human errors are socially defined events for instance; a perfectly reasonable action for one person might be a disastrous failure for the other (Hollnagel, 1998). Whereas risk assessment is a quite broader term usually carried out to deal with organisational and environmental factors but ignores the personal factors that could lead to human errors. The literature reviewed above has made it obvious to embrace HRA for human error management however, this technique could not make its way into the construction industry.

One of the main limitations of the use of HRA in the construction industry is the complexity of HRA methods (Schiraldi, 2013). Each of the HRA methods has its limitations as well as different calculation techniques to analyse the task (HSE, 2009). Therefore, safety professionals in construction are reluctant to use HRA methods because of their sophisticated nature. Moreover, many of the HRA methods require expert human reliability analysts to calculate the human reliability analysis of complex tasks. Such a person is usually an engineering psychologist, human factor specialist or ergonomist. Therefore, the risk assessment team needs to include a person with human reliability assessment expertise as the construction safety professionals are usually unfamiliar with HRA. Another limitation is the working style of the construction industry which traditionally operates around efficiency rather than reliability, however, HRA encourages a culture of reliability instead of efficiency (French *et al.*, 2011). Another limitation found is the unavailability of human reliability analysis methods specifically made for the construction industry. Although few efforts have been made as mentioned above, however, no robust HRA with practical usage has been found in the literature.

3.4. Technology Interventions in Health & Safety in Construction

The foregoing literature has stated all the paramount causal factors of accidents on construction sites responsible for ineffective safety performance. In response to the shortcomings of traditional safety measures, this study reviewed the contemporary methods and tools being practised in safety-critical industries and identified a method integrated with advanced technologies to overcome the causal factors. Park and Kim (2013) stated that the Architecture, Engineering, Construction (AEC) and Facility Management (FM) industries heavily rely on visual communication, and can be benefited enormously from advancements in virtual technology. For instance, the use of building information modelling (BIM) has changed the way of planning and management approaches in the construction industry (Zhang *et al.*, 2013b). BIM applications are not limited to visualization however, it facilitates communications and collaborations for better planning, design and management. Similarly, BIM-based safety methods have also been introduced in the construction industry in the past decade, however, most of them were focused on risk assessment. For instance, Ganah and John (2017) developed a method to integrate project planning and safety management through BIM. Similarly, Hongling et al. (2016) developed a tool to integrate BIM and safety rules to identify unsafe factors during the design phase of the construction project.

Consequently, many other technologies have made their way to the construction industry; the most prominent ones found in the literature are 3D & 4D technologies, geographic information systems (GIS), immersive technologies, web-based safety management and monitoring technologies, digital technologies and unmanned aerial systems (UAS) for safety management and risk assessment (Chantawit *et al.*, 2005a; Bansal, 2011a; Greuter *et al.*, 2012; Teizer, Cheng and Fang, 2013c; Bhoir and Esmaeili, 2015; Li *et al.*, 2015, 2018a; Zhang *et al.*, 2015b; Azhar, 2017; Melo *et al.*, 2017a). The concept of automation has also prevailed in the construction industry in recent years with the advancement in technology. Automation in the construction industry has distinct interpretations at different levels in the construction industry (Chen *et al.*, 2018). For instance, while most designers see this as a way to automate project planning and design, construction contractors see it as using robots to complete tasks on site. Similarly, different definitions exist in the literature on automation in the construction industry. For example, Bock (2015) defined ‘construction automation’ as a new set of technology and processes that will fundamentally alter the course and concept of construction. On the other side, contractors devised a more specific definition, referring to "construction automation" as a machine-controlled construction technology for deploying robotic systems in the construction area (Jung, Chu and Hong, 2013).

Previous research found that the majority of construction-related accidents were caused by a lack of preventive and proactive actions such as workforce training, risk assessment and hazard identification, safety awareness and education, and so on (Park and Kim, 2013b). Building Information Modeling (BIM), Virtual Reality (VR), Augmented Reality (AR), and other game engine-based Mixed Reality (MR) solutions have been embedded into the safety management systems to overcome the pertaining challenges (Chi, Kang and Wang, 2013). These advancements in immersive technology have benefited enormously in many industries like education, marketing, entertainment, and healthcare to improve the learning experience, cognitive ability, creativity and engagement (Suh and Prophet, 2018). Conscientiously, immersive technology has also found its applications in the construction industry for visualization and planning purposes.

As aforementioned, many researchers already have tentatively implemented virtual reality for better visualization, planning, collaboration, communication, training and safety enhancement areas. For instance, Hongling et al. (2016) developed a game for construction safety training by allowing the trainees to navigate and perform construction operations and enhance their safety perception. Li, Chan and Skitmore (2012) used the game engine to develop a VR training program that allowed the users to practice the process of safe tower crane dismantlement and other teaching and learning purposes. Similarly, Le et al. (2015) designed a game for the students to learn about safety materials, rules, and regulations through interaction using virtual reality. Similarly, Guo, Yu and Skitmore (2017a) studied the application of visualisation technologies in construction safety and discovered that visualisation technology may efficiently enhance safety training, enable job risk area identification, and prevention of accidents in a visible, interactive, and cooperative manner. Based on the broad applications of immersive technologies for visualization, training and hazard analysis, this research aimed to further explore the immersive technologies for the development of the proposed immersive safety management framework.

3.4.1. Immersive Technologies (VR/AR) Overview

Soliman, Peetz and Davydenk (2017) defined immersive technology as a technology that blurs the barrier between the physical and virtual worlds, creates an immersive feeling and enhances the realism of virtual encounters. An immersive virtual environment (IVE) surrounds the user perceptually, boosting the user's impression of the presence or real presence within it. The goal of virtual reality (VR) simulation is to create immersive settings in which users may get unique insights into how the actual world operates (Kim *et al.*, 2013; Guo *et al.*, 2018; Suh and Prophet, 2018). The concept of VR appeared more than 50 years before the invention of the first immersive "Human-computer interaction" (HCI) model called the "Man-machine graphical communication system" which was later named virtual reality (VR) (Lakaemper and Malkawi, 2009; Li *et al.*, 2018a). Scholars have since proposed many taxonomies to explain where a rigorous VR idea should be placed on the continuum of reality to virtuality (RV) proposed by Milgram and Colquhoun in 1994 shown in Figure 3.14 below (Skibniewski, 2014). This reality-virtuality continuum represents four Reality-Virtuality experience levels based on the degree of blending that various electronic display technologies can achieve.

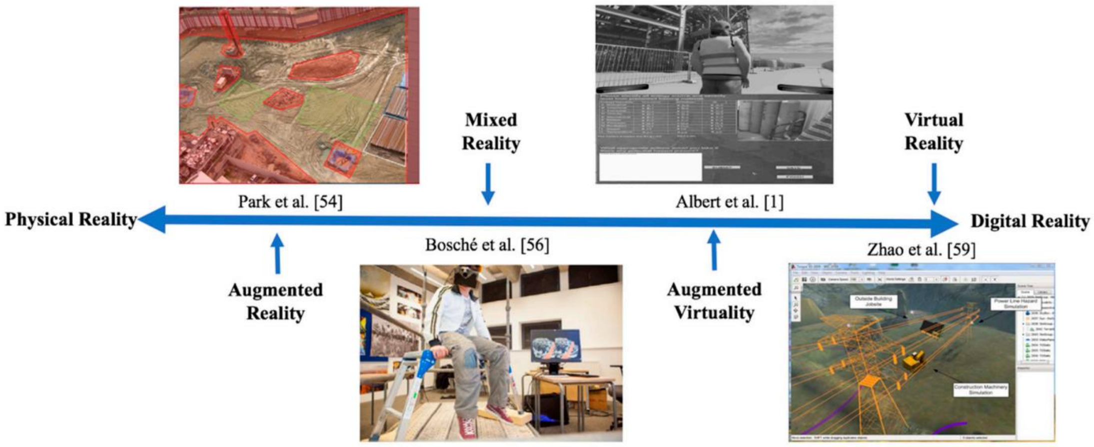

Figure 3.14: Milgram and Colquhoun's Reality-Virtuality Continuum (Skibniewski, 2014)

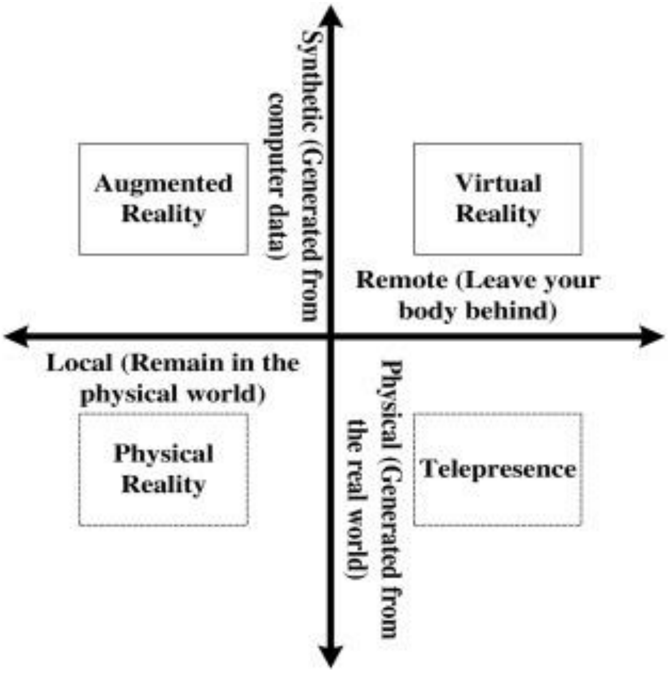

Figure 3.15: Benford's Classification of Virtual and Real Space (Li et al., 2018a)

Furthermore, to differentiate the boundaries between reality and virtuality; another taxonomy has been introduced by Benford shown in Figure 3.15 (Li *et al.*, 2018a). Benford classified four spaces based on whether a group of users can access virtual things from their local space and whether a space is synthetic or dependent on the physical world. The application of immersive technologies covers broad areas from visualization to perception developments with the aid of different technologies. Moreover, Virtual reality (VR) aims to replace a user's perception of their surroundings with the help of a computer-generated artificial 3D environment. Similarly, augmented reality (AR) aids users' perception by bringing virtual information into the real world (Carmigniani *et al.*, 2011). AR is an emerging technology that combines images of virtual items with the actual environment. AR technology could achieve the goal of augmenting a person's perception of virtual prototyping with actual entities by putting virtually simulated prototypes into the real world and producing an augmented scene.

Various visualisation approaches, such as VR and related development, such as AR, have been used to enrich learning experiences since the early 2000s. Virtual reality has proven to be a useful technique for improving learning and visualising abilities (Wang *et al.*, 2018). Furthermore, traditional 3D approaches to education and training rely on the use of a mouse or keyboard to engage with the computer-generated structural form (Park *et al.*, 2016). Therefore the role of immersive technologies has been critical to addressing the prevailing challenges raised by the rapid changes in the technology used in the industry by offering adequate training programmes to improve employees' daily tasks which have become increasingly crucial. Traditional training methods, such as computer-aided learning, are incapable of preparing decision-makers to deal with numerous situations, thus immersive technologies enable cognitive learning by immersing the employee in the real-time situation. However, the application of immersive technologies is not limited to visualization and immersive learning but extends to behaviour development through cognitive reading (Menin *et al.*, 2016).

3.4.2. Virtual Reality (VR) Development in Immersive Technology

VR is a computer-generated scenario that creates a realistic experience that may be engaged in a presumably real or physical way by a person utilising sophisticated electrical equipment (Muhanna, 2015). To display important data and analyses in immersive areas, it has mostly relied on interactive 3D graphics, user interfaces, and visual simulation (VS) (a graphical representation of devices and objects of interest employing graphical languages). Because of its ability to stimulate involvement and motivation, virtual reality (VR) is widely employed in the sectors of education and training (Freina and Ott, 2015). Virtual reality has applications in safety training as well as embedding safety perception by developing computed-aided safety scenarios. VR offers the possibility of travelling safely around risky situations, learning to manage emotions while experimenting with the best solutions, far away from the real dangers, for vocational training aimed at adult workers who otherwise could not be physically reached due to constraints such as time, physical inaccessibility, and ethical concerns (Freina and Ott, 2015).

There is a diverse set of technologies available, including computer interfaces, portable devices, 3D graphics, and sensors all of which are required to create immersive environments such as head-mounted displays (HMDs) (Bernal *et al.*, 2022). The user can be completely immersed in the virtual environment with the help of these technologies. Moreover, these technologies also help users experience more immersion, presence, and interactivity. The degree to which a user can engage with the simulated world is referred to as interactivity. Similarly, the subjective sensation (illusion) of being in one place is known as presence, and it is closely linked to immersion. Immersion, from a technological standpoint, refers to a system's ability to provide a comprehensive and expansive environment, as well as a vivid perception of reality. As a result, display resolution, stereo capability, a wide field of view, tracking devices, and input devices all contribute to the illusion. Immersion, from a psychological point of view, is a mental and emotional state in which the user perceives sensory isolation from the real world (Sepasgozar, 2022). Thus, immersive virtualisation technology gives the impression that the user is physically, cognitively, and emotionally present in a virtual 3D environment.

3.4.3. Virtual Reality (VR) System Development

Virtual reality systems are created by the interaction of three components: computer, software and peripheral hardware (Frank Moore and Gheisari, 2019a). Several software tools have been used by professionals for the modelling of the virtual world integrated with the hardware tools to develop a sense of immersion. The hardware serves as the primary interface between the user and the virtual or augmented world such as HMD and CAVE (Sacks, Perlman and Barak, 2013a). Figure 46 below shows the basic requirements for the development of a virtual reality system. This starts with the development of scenarios using 3D modelling software, however, not limited to the environment but the objects and characters in the virtual world. In the construction industry, several tools have been used for 3D modelling that is required for virtual environment development. In the construction industry, the most commonly used 3D tools are BIM 3D, Revit, 3D Max, Maya, and Blender which can be used for 3D modelling in VR development. Figure 3.16 shows the 3D modelling of a construction scenario that can be used in developing an immersive environment.

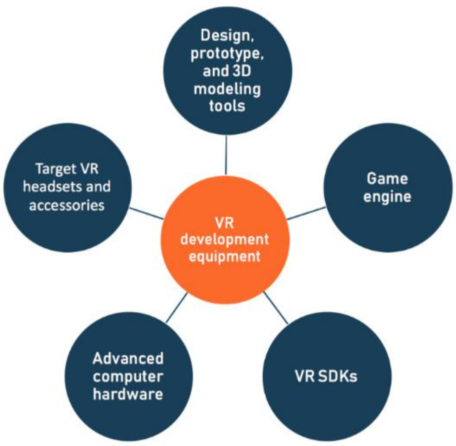

Figure 3.16: VR Development Requirements (Frank Moore and Gheisari, 2019a)

Subsequently, along with the conventional modelling software, immersive development requires another set of software tools called Game-Engines which converts 3D models into immersive environments. Moreover, a game engine is an absolute part immersive tool for creating interactive virtual reality experiences (Bernal *et al.*, 2022). Game engines are special software that use programming and graphic design skills to create rich, immersive, and realistic worlds. These tools are aimed at connecting all software and hardware technologies to create an essence of immersive existence. Moreover, along with the integration, the essential purpose of game engines is to develop functions and systems using programming which can be executed in the virtual world. Figure 3.17 below demonstrates the development of VR using encompassing different software and hardware tools. Several tools have been usually utilised for the development of a virtual environment. First of all, the virtual environment is developed utilizing modelling tools such as Revit, 3D Max, Maya and Blender followed by the game engine where most of the development is carried out. The training simulations, different levels of complexities and scenario-based assessments are designed in the game engines. For instance, Bernal et al. (2022) developed a virtual reality training game utilizing Revit along with Unity3D for safety training.

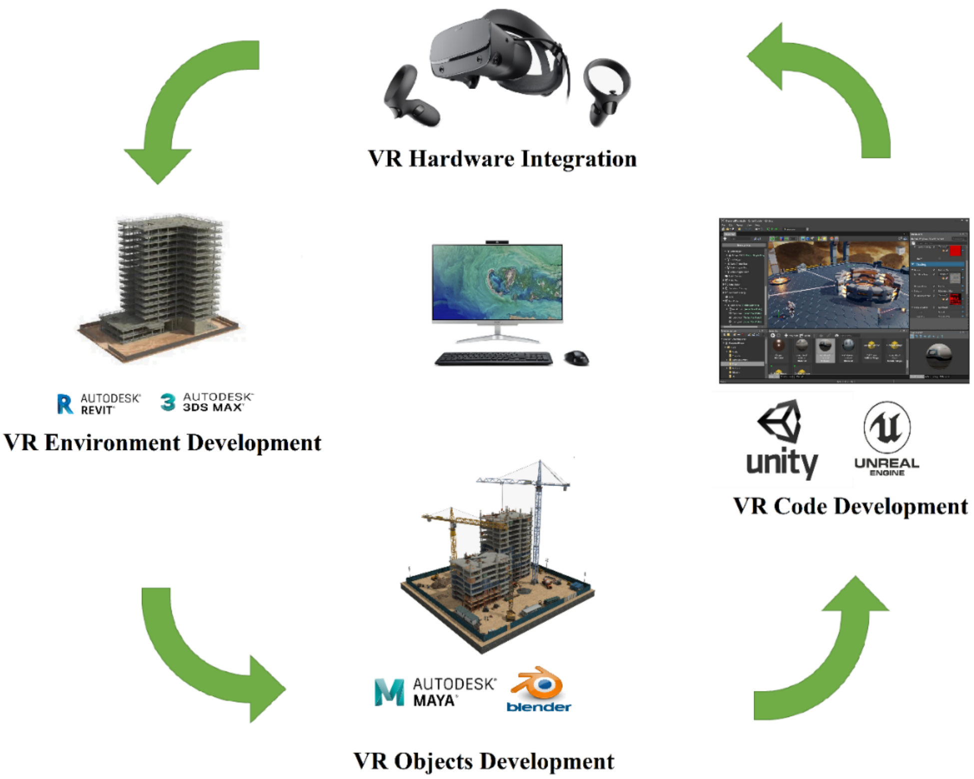

Figure 3.17: VR Development Process (Bernal et al., 2022)

Along with the game engines, several hardware tools are utilized to develop a sense of immersion. The Cave Automatic Virtual Environments (CAVE) was the first immersive instrument introduced by researchers that facilitate immersion, in which the user is in a chamber with projection screens on all four walls and the floor. Afterwards, VR glasses and head-mounted displays (HMD) further improved virtual reality with the introduction of sensory instruments. CAVE environments are still quite expensive, they require a dedicated room, and they are not easily transportable (Freina and Ott, 2015). Because of these characteristics, they are unlikely to be widely used in education and training. Thus, CAVE technology is typically used in cultural heritage education (Ott and Pozzi, 2008). However, on the other side, wearing 3D glasses, the user feels as though he is floating in the simulated world, free to move around. Moreover, VR glasses or other types of Head Mounted Displays (HMD) can easily give the visceral sensation of actually being in the simulated world when combined with headphones. For the complete immersive sense, all of our five senses should be involved in the development of the virtual world. However, most VR environments today don't handle all of them, instead focusing on two of them: sight and hearing. This research aimed to explore immersive technologies for the development of a safety management framework. It is clear from the above literature that immersive technology can immensely benefit the found safety issues in the construction industry by developing immersive VR from human reliability assessment and training simulations.

3.5. Considerations in Developing the Framework

Several accident causation models developed since the 1960s were critically examined in this chapter to identify the developments in the area of human error. The accident causation models aimed at investigating root causes of accidents have been extensively used in the past for accident investigations to help reduces accidents in many industries. Many researchers in recent years have investigated historical advancements in accident causation models to develop safety management systems. For instance, accident causation models have been classified into simple linear models, complex linear models and complex non-linear models. The advanced accident causation models advocate adopting a systematic approach to deal with inevitable accidents in complex dynamic socio-technical systems. Several accident causation models have been explored in this research, for instance, the swiss-cheese model, SDK model and Birds Model which identify latent and direct causes of accidents. Moreover, the swiss-cheese model influenced this study and the proposed model has been developed based on this model by incorporating a human error barrier within the safety management system. These models contributed substantially to the research in identifying the proximal, latent and influencing factors that helped the research to understand the accident mechanism as well as highlighting the key factors to focus on to manage human factors.

3.6. Chapter Summary

This chapter examined the most prominent factor that causes most of the casualties to further explore the methods used in several industries to minimize or eliminate the outstanding effects. Through a rigorous literature review, the research identified human factors as the most noteworthy cause of accidents in the construction industry. The 'Human Factor is commonly defined as the interaction of human beings with each other and with the workplace in any workplace. Due to technological advancement, the construction industry has become a more complex and dynamic socio-technical system that signifies the importance of the human factor. The literature also reviewed the accident causation theories to understand the process involved in the accidents. Research further revealed that human factors originate because of the personal traits of the workers in a system. Hence, the research explored the methods which have been used by the researchers to mitigate the impacts of human errors and identified the potential methods and techniques which helped to develop the proposed framework for safety management.

Subsequently, this chapter also examined human reliability analysis (HRA) methods used as a prevailing practice in safety-critical industries as a systematic technique to identify, quantify and mitigate human error in complex safety systems. The HRA approach has successfully been used in several industries to control the personal characteristics and behavioural aspects of the workers in a human-machine system. The complexities of these methods have been identified as one of the prominent reasons these methods couldn’t find their way into the construction industry. However, the study of human reliability analysis was the key milestone for the research as it steered the research to develop the safety management framework based on human reliability assessment/analysis.

Lastly, the chapter reviewed the technological advancement in construction as well as other industries. Technological advancements have helped many industries to overcome the prevailing issues, especially safety issues, however, the construction industry could not yet fully benefit from the advanced technologies. This research has explored state-of-the-art technologies that have been used in construction and found automation, visualization and immersive technologies among the top trends in the construction industry. Moreover, in-depth insight into immersive technologies has been carried out in pursuit to develop a technological gateway for safety management in the construction industry. Immersive technology has been found pertinent to developing a safety management framework. Therefore, to accomplish the study's aim the applications of immersive technologies have been reviewed and incorporated into the proposed safety management framework.

Chapter 4: Research Design and Methodology

4. Introduction

The previous chapter carried out a succinct accident causation study as well as reviewed the H&S methods used in safety-critical industries to propose a method to manage human factors in the construction industry. This chapter unveils the research methodology practised to conduct this research. The chapter also presents the data collection methods, research approach used for primary data collection and analysis appropriate to achieve the research objectives. Moreover, this chapter explains the connection between the adopted research methodology and research philosophies.

4.1. Research Methodology

The term ‘research’ has been defined in the Oxford dictionary as ‘the systematic investigation into and study of materials and sources to establish new facts and conclusion’. Uusitalo (2014) stated that the research carried out can be comprehended in terms of the research philosophy adopted, the research strategy employed, and thus the research instruments used in the pursuit of a goal. Similarly, a range of interpretations has been derived for the term ‘research methodology’ in different scientific fields. The research methodology is the approach and the login to the principle and procedures of scientific research (Fellows and Liu, 2015). Moreover, Fellows and Liu (2015) further stated that the research involves systematic and careful investigation of research questions that contribute to the addition of knowledge. Similarly, Fernandez (2020) defines the research methodology as a systematic and scientific search for appropriate knowledge on a specific topic. Similarly, Kumar and Phrommathed (2005) referred to a research methodology as the approach that comprises philosophy and methods to support the investigation. Therefore, a research methodology comprises research philosophy, approach and techniques used for the scientific investigation of an issue (Knight and Ruddock, 2009; Fernandez, 2020).

Researchers in the different research domains usually adopt customised research methodologies however, there are two kinds of research methodologies known as 'Nested research' and 'Onion Research'. The former is a simplified research methodology developed by Kagioglou (1998) in which the final research tools/techniques are selected by narrowing down the research philosophies and the adopted research approach. The nested methodology has three layers, where the research philosophy guides and energises the research approach and research techniques from the outer layer as shown in Figure 4.1.

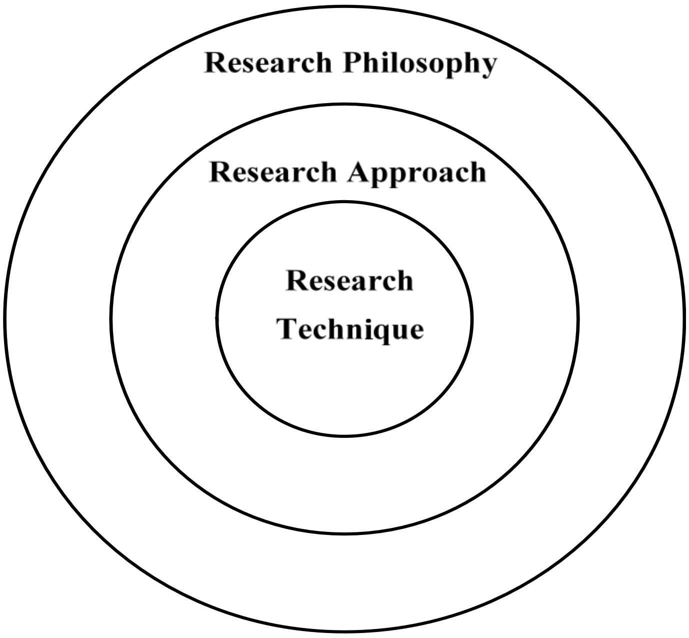

Figure 4.1: Nested Research Philosophy (Kagioglou, 1998)

Alternatively, the latter research methodology developed by Saunders, Lewis and Thornhill (2013) for business-related research comprises multiple layers like an 'onion' to assist to formulate an effective research methodology shown in Figure 4.2. The prominent layers in the 'research onion' are; research philosophy, approach, strategies, time horizon and data collection starting from outer to inner. Research onion provides an extensive explanation of the key layers or stages that must be accomplished to develop a robust methodology (Melnikovas, 2018). Within this research onion, the starting point is the delineation of the main philosophy, choosing appropriate research approaches, methods, strategies, and time horizon as well as identifying the data collection and analysis technique which altogether connects the research logic to the research design.

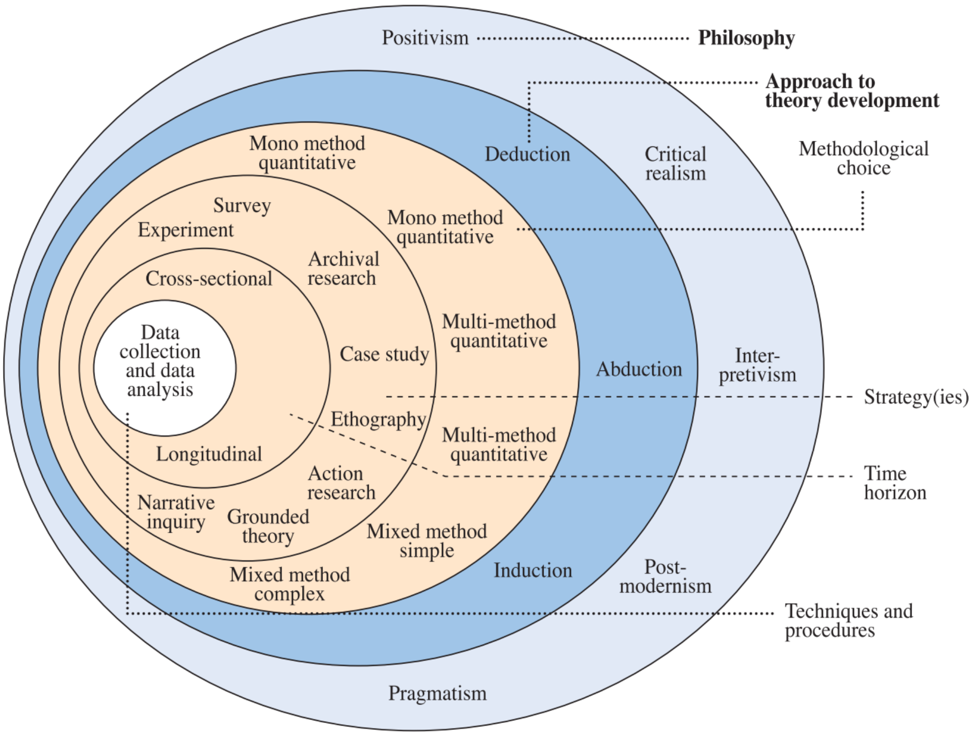

Figure 4.2: Research Onion Methodology (Saunders, Lewis and Thornhill, 2013)

The six main layers of the research onion are described below (Saunders, Lewis and Thornhill, 2013);

1. *Research Philosophy:* This layer form the research basis through the delineation of ontology, epistemology and axiology of the research.
2. *Research Approach:* This is built on the adopted research philosophy and usually includes deduction, induction or abduction approaches.
3. *Methodological Choice:* Followed by the selection of research approach this layer determines the selection of qualitative, quantitative or mixed methods.
4. *Research Strategy:* Identify the research strategy to collect and analyze data which includes: survey, experiment, case study, ethnography, action research, archival research or narrative exploration.

5. *Time horizon:* Defines the timeline for the research that involves cross-sectional or longitudinal research.
6. *Techniques/Tools:* This layer involves the selection of appropriate techniques/tools for data collection and analysis.

Each of these layers is examined below and an adopted philosophical assumption has been identified for this research.

4.1.1. Research Philosophy

When carrying out the research, the researchers must implement the underlying philosophical perspective (Gray and Malins, 2004). These underlying philosophical assumptions delineate the nature of reality (ontology) for the pursuit of knowledge (epistemology) considering the ethics of research (axiology) (Fellows and Liu, 2015; Melnikovas, 2018). These philosophical assumptions are described below;

4.1.1.1. Ontology

Ontology is a philosophical viewpoint that refers to the nature of reality or what holds a reality (Saunders, Lewis and Thornhill, 2013). De Vreede (1998) states ontology is the way we define reality. The context of a paradigm or the reality of a belief system is represented by ontology. An ontology could be characterized as either ‘objectivism’ or ‘subjectivism’. These ontological assumptions are also mentioned as ‘Realism’ and ‘Idealism’ by (Burrell and Morgan, 1979). ‘Objectivism’ or ‘Realism’ refers to the position where knowledge exists in the reality external of the social actors whereas, ‘Subjectivism’ or ‘Idealism’, on the other hand, drives the knowledge and its existence from the perceptions and the subsequent actions of social actors (Alan Bryman, 2012).

As the research aims to identify the root causes of accidents to establish a robust method/framework for improved safety, therefore, this research rules out the realistic ontological position. Furthermore, this research revolves around accidents in the construction industry and the ontological question of this study would be ‘how do accidents happen?’ which takes a subjective standpoint. Hence, this research aligns more towards idealism or subjectivism to interpret knowledge mainly through social interaction. Moreover, by taking this position, these research outcomes were developed based on the participant's opinions, views, and knowledge about the research questions.

4.1.1.2. Epistemology

Epistemology, as mentioned above, is mainly concerned with sources as well as the nature of knowledge and the relationship between research and researcher. Saunders, Lewis and Thornhill (2013) reported that epistemology shapes what develops satisfactory knowledge in the specific domain of study. It emphasizes the acceptability of knowledge in the field of study, i.e. how knowledge is acquired (Alan Bryman, 2012). The key concern of epistemology is explaining the relationship between knowledge and researchers during the research (Laura Killam, 2013). In conducting research, there are four philosophical perspectives to epistemology which include ‘positivism’, ‘interpretivism’ (also known as social constructivism), ‘realism’, and ‘pragmatism’.

Positivism is a type of philosophy that believes data can be acquired from observations (Michael Levin, 1998). Alternatively, interpretivism proposes that knowledge can only be identified through subjective interpretations of reality (Crotty, 1998; Saunders, Lewis and Thornhill, 2013). Lastly, pragmatism is another philosophical paradigm that is called the Philosophy of Common Sense. Pragmatism is action-oriented research philosophy that argues concepts are only useful when they support actions (Kelemen and Rumens, 2008). Moreover, pragmatism lies between two extreme philosophical positions i.e. positivism and interpretivism. The ontological, epistemological and axiological position of the discussed philosophies is highlighted in Table 4.1 below.

Subsequently, in terms of epistemological position, considering two epistemological extremes, ‘positivist’ and ‘social constructivism’, this research is deemed more aligned toward social constructivism. Moreover, this study is exploratory by nature and interprets knowledge based on unarticulated knowledge from H&S intellectuals and exploits both qualitative and quantitative research paradigms for data collection to investigate the issue and present a method to overcome it. Hence, based on the explored epistemological approaches to dealing with the issue and the selected methodological approach, this study best fits under the pragmatic epistemological approach.

Table 4.1: Research Philosophies Comparison (Saunders, Lewis and Thornhill, 2013)

	Positivism	Realism	Interpretivism	Pragmatism
Ontology: *the researcher's view of the nature of reality or being*	External, objective and independent of social actors	Is objective. Exists independently of human thoughts and beliefs or knowledge of their existence (realist), but is interpreted through social conditioning (critical realist)	Socially constructed, subjective, may change, multiple	External, multiple, view chosen to best enable answering of research question
Epistemology: *the researcher's view regarding what constitutes acceptable knowledge*	Only observable phenomena can provide credible data, facts. Focus on causality and law like generalisations, reducing phenomena to simplest elements	Observable phenomena provide credible data, facts. Insufficient data means inaccuracies in sensations (direct realism). Alternatively, phenomena create sensations which are open to misinterpretation (critical realism). Focus on explaining within a context or contexts	Subjective meanings and social phenomena. Focus upon the details of situation, a reality behind these details, subjective meanings motivating actions	Either or both observable phenomena and subjective meanings can provide acceptable knowledge dependent upon the research question. Focus on practical applied research, integrating different perspectives to help interpret the data
Axiology: *the researcher's view of the role of values in research*	Research is undertaken in a value-free way, the researcher is independent of the data and maintains an objective stance	Research is value laden; the researcher is biased by world views, cultural experiences and upbringing. These will impact on the research	Research is value bound, the researcher is part of what is being researched, cannot be separated and so will be subjective	Values play a large role in interpreting results, the researcher adopting both objective and subjective points of view

4.1.1.3. Axiology

The role of ethics and values in the research process is referred to as Axiology. This is the position within the research philosophy that judges the research value (Saunders, Lewis and Thornhill, 2015). Easterby-Smith, M., Thorpe, R. and Jackson (2012) state axiology as the third component of the research philosophy that identifies whether the reality is value-free or value-driven. Moreover, the axiological assumptions concern the nature of value and the foundation for the value judgement (Kulatunga, Amaratunga and Haigh, 2007). Hence, as mentioned above, this spectrum ranges from 'value-free' where no value judgement is imposed on the research and 'value-laden' where value is imposed on the subject by the researcher. As this research aims to build the outcomes based on subjective interpretations, further, the research outcomes are purely based on the researcher's values which help to determine what is real facts and knowledge. Hence, the research Figure 4.3 shows the philosophical position of this study.

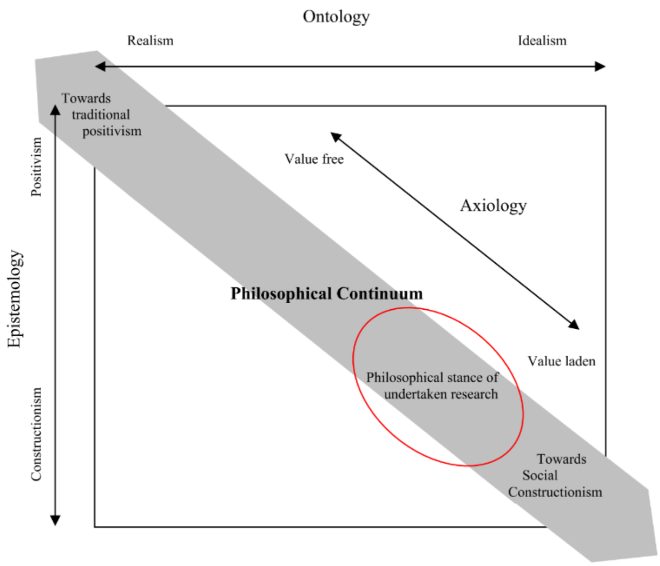

Figure 4.3: Continuum of Adopted Research Philosophy

4.1.2. Research Approach

After underpinning the philosophical positioning of this research, the research approach is the following layer in the research onion which typically is dependent on the adopted philosophical paradigm. Saunders, Lewis and Thornhill (2013) defined the research approach as how to establish knowledge/theory. Furthermore, Thurairajah, Haigh and Amaratunga (2007) stated that the research approach is about conducting research activity for data collection in the most appropriate way to achieve the research aims. Saunders, Lewis and Thornhill (2013) categorised the research approach into 'deductive', 'inductive' or 'abductive' research. A detailed commentary on each research approach is provided in the sub-sections below.

4.1.2.1. Deductive Approach

As noted above, the deductive approach involves the development of a theory based on the rigorous test by the researcher (Saunders, Lewis and Thornhill, 2013). Saunders, Lewis and Thornhill (2013) state that the deductive approach is typically used for realistic ontological research. Moreover, the deductive approach drives from broader to more particular perspectives and is also known as the top-down research approach (Hyde, 2000). Robson and McCartan (2002) mentioned five stages to carrying out a deductive inquiry as shown in Figure 4.4. As this research entails a subjective ontological position therefore the deductive approach won't be applicable to this research.

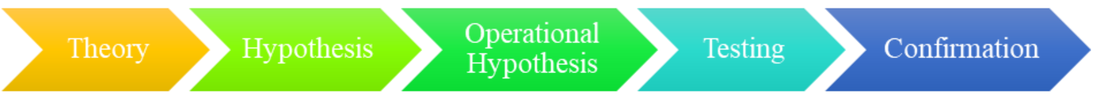

Figure 4.4: Deduction Approach Steps (Robson and McCartan, 2002)

4.1.2.2. Inductive Approach

The inductive approach is a theory-building process, that starts with the observations of a specific perception and seeks to build a theory/generalisation about the phenomenon under investigation (Hyde, 2000). Contrary to the deductive approach, the inductive approach involves the development of a theory based on perception. This approach is frequently used in the social sciences and supports subjective/idealistic ontological research and is also referred to as the 'bottom-up' approach to drive data from particular to generic knowledge. Figure 4.5 illustrates the steps involved in the inductive research approach. Furthermore, for a better understanding, Saunders, Lewis and Thornhill (2013) suggested the following differences between deductive and inductive approaches shown in Table 4.2.

Figure 4.5: Inductive Approach Steps (Hyde, 2000; Teddlie and Tashakkori, 2009; Alan Bryman, 2012)

Table 4.2: The comparison between deductive and inductive inquiries

Deduction emphasises	Induction Emphasises
• scientific principles • moving from theory to data • the need to describe causal relations between variables • quantitative data collection • the use of controls to confirm the validity of data • the operationalisation of ideas to ensure the accuracy of definition • a highly organised approach • researcher independent of what is being researched • the need to select samples of adequate size to generalise conclusions	• getting an understanding of the meanings social actors attach to events • a close understanding of the research background • qualitative data collection • a more flexible approach to allow changes in research weight as the research progresses • an understanding that the researcher integral is part of the research process • less pressure with the need to generalise

This research builds its understanding on the perception of the health and safety intellectuals in the construction industry about health and safety practices in the construction industry, therefore, this comfortably adopts an inductive research approach as mentioned by (Hyde, 2000) for the development of a Health and Safety management framework. Moreover, the implemented research is researcher-driven holds an idealistic ontological position and utilizes qualitative research methods for data collection and analysis, hence, this research could be underpinned as inductive research. Hence, the inductive research approach has been adopted for this research that exploits both deductive as well as inductive approaches for the best outcomes.

4.1.2.3. Abductive Approach

Abduction is another position in the research approach that argues that theory can be developed from inference, starting from observation as the basic concept for further research (Melnikovas, 2018). He further noted that abductive inference is the best conclusion or guess based on available knowledge. The abductive technique is based on the observation that most major scientific breakthroughs did not follow a pattern of pure induction or pure deduction (Kovács and Spens, 2005). As this research is taking an inductive approach therefore this research approach can not be applied to this study.

4.1.3. Methodological Choice

It is crucial to underpin the research methodology after adopting a research approach that defines how the research intends to acquire knowledge (Alan Bryman, 2012; Saunders, Lewis and Thornhill, 2013). The research methods highlight the ways to answer the research questions. The research methodologies are usually classified research methodologies as qualitative and quantitative (Saunders, Lewis and Thornhill, 2013). However, many researchers have used a mixed-methodologies strategy, which combines qualitative and quantitative methods in the same study. Moreover, these terms are commonly used in business and management research to distinguish between both data collection and analysis techniques. The decision to choose any methodology would be based on the study's goal as well as the type and availability of data for the research. Hence, the research methodology is either qualitative or quantitative or mixed based on research objectives (Saunders, Lewis and Thornhill, 2013). These research methodologies are examined below to clarify the difference and select an appropriate method for this study.

4.1.3.1. Qualitative Methodology

Qualitative research methodology uses an inductive approach, which is well-suited for research that seeks a deeper understanding of topics that are primarily related to the study of the implications of human experience, rather than testing predictions (Alan Bryman, 2012). Qualitative research concerns understanding and exploring the meaning of the research questions from the participant's viewpoint (Creswell, 2009). Furthermore, this methodology deals with the ‘why’ and ‘how’ types of questions (Fellows and Liu, 2015). This implies that it is based on interpretive or critical social science and takes a non-linear approach to research. Creswell (2009) further stated that the qualitative method examines the meaning individuals or groups give to social or human problems, starting with assumptions, worldviews, and various theoretical lenses.

4.1.3.2. Quantitative Methodology

The quantitative research method is often related to true science that includes experimentation as well as correlation studies (Creswell, 2009). Quantitative research methodology deals with testing the theories by investigating the relationship between the research variables. Furthermore, this research methodology is considered a positivist research paradigm as mentioned in section 4.2.1. Quantitative methodology is primarily used synonymously with data collection methods (such as questionnaires) or data analysis procedures (such as graphs or statistics) that generate or use numerical data (Saunders, Lewis and Thornhill, 2013). Similarly, Creswell (2009) stated that this methodology consists of the application of mathematical and statistical techniques to identify facts and causality. This follows a deductive research approach based on hypothesis or theory testing and consists of variables measured by numbers and analyze using statistical procedures to determine whether the theory or hypothesis remains correct.

4.1.3.3. Mixed-method Approach

Johnson and Onwuegbuzie (2004) defined a mixed-method approach as; “a study class in which researchers combine or mix qualitative and quantitative research methods, approaches, concepts, or languages in a single study”. Creswell (2009) also described mixed methods as “a methodology that combines or links both quantitative and qualitative methods to carry out the inquiry”. Similarly, Saunders, Lewis and Thornhill (2013) referred to multiple methodologies as employing both quantitative and qualitative data collection techniques and analytic procedures in a study design. He further subdivided the multiple-method approach as ‘multi-method’ and ‘mixed-methods’ based on data collection and analysis techniques. Mixed method research employs both quantitative and qualitative data gathering and analysis techniques and procedures, either simultaneously (parallel) or sequentially (one after the other), however, does not integrate them.

Mixed-model research incorporates qualitative and quantitative data-gathering techniques and analysis procedures, as well as qualitative and quantitative approaches at other stages of the research, such as the development of research questions. The advantage of using a mixed-method approach is that it could assist in emphasising theoretically credible answers to the research question by removing practical or cognitive hurdles associated with the study (Creswell, 2009). Although a mixed-methods strategy can improve data collecting, the researcher must first concentrate on the research question, goal, and context (Johnson and Onwuegbuzie, 2004; Fellows and Liu, 2015). Mixed-method research can be classified as Triangulation, Embedded, Complementarity, Explanatory or Exploratory (Johnson and Onwuegbuzie, 2004; Creswell, 2009; Alan Bryman, 2012; Saunders, Lewis and Thornhill, 2013) shown in Table 4.3 below.

Table 4.3: Mixed-Method Research Types

Mixed-Method Type	Description
Triangulation	Combining both qualitative and quantitative research methods to better examine the research problem.
Embedded	Using either quantitative or qualitative research to answer research questions in either predominantly quantitative or qualitative research.
Complementarity	Use both qualitative and quantitative research methods to examine complementary views about a particular aspect of research.
Explanatory	A mixed-method approach uses qualitative data to explain quantitative results.
Exploratory	A Mixed-method approach utilizes quantitative data to explain a relationship found in qualitative data.

As this study utilises both qualitative and quantitative approaches for framework development and validation, therefore, a mixed-method approach was adopted to fulfil the purpose to investigate the research problem as well as to develop a framework to rectify the problem. Furthermore, exploratory mixed-method research has been conducted to first collect quantitative data followed by qualitative interviews to validate the research outcomes. To answer the research questions, the quantitative research has been carried out in the first stages using the questionnaire survey to explore the research problem and develop a novel framework followed up by semi-structured interviews to validate the research findings. Hence, an explanatory mixed-method research approach has been found as the most appropriate research method for this study to critically examine the research questions and propose a novel framework to rectify them.

4.1.4. Research Strategies

On the successful selection of the research methodology, the next layer is to reveal the research strategy in the research onion by Saunders, Lewis and Thornhill (2013). Research strategies are the essential components introduced in the research plan included in the research design to collect and analyse data. Research strategy is also referred to as 'how' researchers proposed to answer the research questions and 'how' to implement the research methods. The list of research strategies listed by Saunders, Lewis and Thornhill (2013) are; experiments, surveys, action research, interviews, grounded theory and ethnography. Therefore to develop a robust research methodology to answer the research questions, it is equally important to choose an appropriate research strategy. Furthermore, the literature reveals that the researchers associate specific research strategies with specific research philosophies (Pathirage, Amaratunga and Haigh, 2005). For instance, ethnography is usually associated with an interpretivism epistemological position, while surveys and experiments are often linked with positivism (Sexton, 2004). Similarly, case studies occasionally are used for both positivism and interpretivism research (Saunders, Lewis and Thornhill, 2013). However, regardless of the selection technique, the adopted strategy should be able to achieve the research objectives and aims. Some of the commonly used research strategies have been examined below;

4.1.4.1. Surveys

Surveys are a widely acknowledged research strategy that requires information from participants through questionnaires or structured interviews. This research strategy provides a means to collect answers from a large number of participants in a structured format, using statistical analysis (Creswell, 2009; Saunders, Lewis and Thornhill, 2013). Moreover, a 'survey' is a non-experimental inquiry that is usually associated with a deductive research approach (Alan Bryman, 2012). Surveys fit into the positivist paradigm as this strategy relies heavily on quantitative data and quantitative analytical methods to find answers to research questions (Oates, 2005). It is typically considered exploratory or descriptive research which is a widely utilised strategy in business and management studies, with the most common questions being who, what, where, how much, and how many. Hence, this strategy allows you to assemble quantitative data that can be analysed statistically with inferential and descriptive statistics.

Considering the explanatory and descriptive nature of this research as well as the usefulness of this strategy in management research, this research strategy was selected to answer the research questions to find out the root causes of accidents and shortcomings in the current safety practices in the construction industry. Furthermore, this strategy allows the collection of data from a specific respondent within the organisation, therefore, fulfilling the research requirement of obtaining data from specific participants (H&S experts) from the construction industry. Hence, a survey was adopted as the research strategy to seek the participant's answers to the research questions. Moreover, the descriptive statistics approach was adopted to analyse the results.

4.1.5. Research Technique

Saunders, Lewis and Thornhill (2013) consider data collecting and analysis to be the most important aspect of research. Research techniques are referred to as the methods/techniques used for collecting data for the underpinned study. Researchers have divided the data collection into three main categories; 'sampling', 'primary data', and 'secondary data' (Alan Bryman, 2012; Saunders, Lewis and Thornhill, 2013). Moreover, some of the key research techniques used in this research are; literature review, questionnaire survey and in-depth semi-structured interviews. These research techniques are examined below;

4.1.5.1. Literature Review

Building your study on existing knowledge is the most crucial yet building block of any academic research activity, regardless of the subject. It enables scholars to comprehend current information, theories, and methodologies, as well as unanswered questions in their domains (Alan Bryman, 2012). Similarly, Tranfield, Denyer and Smart (2003) argued that a literature review is a systematic way of collecting and summarising previous research. As a research approach, an effective and well-conducted review establishes a solid foundation for increasing knowledge and aiding theory development (Webster and Watson, 2002). Therefore, it enables the researchers to critically review the previous knowledge to develop novel theories. Moreover, a literature review may address research topics precisely and comprehensively by combining results and findings from multiple empirical studies (Tranfield, Denyer and Smart, 2003).

Snyder (2019) suggested several essential steps which have to be carried out for an effective and comprehensive literature review which include; (i) designing the review, (ii) conducting the review, (iii) analysing, and lastly, (iv) writing up the literature review. This means that an effective literature review allows the researchers to identify the existing state-of-the-art knowledge, analyse its importance and align their research position and questions accordingly to avoid any duplication of knowledge that already exists. Additionally, several authors have mentioned that conducting a literature review allows scholars to build on current information and broaden their breadth of understanding of their area of interest (Naoum, 2007; Creswell, 2009; Saunders, Lewis and Thornhill, 2013). The literature review has been a very important part of this research as it helped to explore the health and safety problems, highlighted the factors affecting health & safety performance, enlightened the process of the safety management system as well as played a vital role in identifying the research gap and questions. For instance, Chapter 2 of this document examined the current health and safety problems and highlights the systematic literature review on factors affecting health and safety. Similarly, Chapter 3 reviews the most destructive factor causing 80% of the accident in construction sites, and its mechanism and explores the current safety systems to eliminate the factor to identify the research gap. More detail on the literature review is provided in section 4.3.1.

4.1.5.2. Secondary Data

Secondary data, often known as documentary evidence, refers to any material that provides information on the phenomenon under investigation to address research questions and exists independent of the researcher's efforts. Cowton (1998) stated that secondary data is information gathered by others that is not explicitly related to the study subject at hand. It is commonly produced for precise functions apart from the ones of the studies however may be utilized by the researcher for cognitive functions (Newman and Benz, 1998). Fellows and Liu (2015) mentioned several advantages of secondary data documentation over other research methods, for instance; (i) allows the researchers to study past research to use for the underpinned research, and (ii) they may be cost-effective because the facts have already been produced, and (iii) they are non-reactive in the sense that the information provided is not vulnerable to possible distortion as a result of contact between the researcher and the respondent.

Secondary data could be of many different forms as guidance to organisations. Cowton (1998) identified several sources of secondary data, namely, governmental or regulatory body documents, companies' data, the press, and other academic researcher data. This research while exploring the H&S management systems, regulations, best practices and human factors; reviewed several Governmental and Health & Safety Executive (HSC) documents on H&S. The list of documents reviewed explicitly for this research has been listed in Table 4.4 below;

Table 4.4: Secondary Data Reviewed for the Research

Sr #	Document Title	Document Type
01	The Construction (Design and Management) Regulations 2015 (HSE, 2015b)	Governmental / Statutory
02	RR679 - Review of human reliability assessment methods (HSE, 2009)	HSE / Guidance
03	HSG48 - Reducing error and influencing behaviour (HSE, 2018)	HSE / Guidance
04	HSG245 - Investigating accidents and incidents (Garrett and Teizer, 2009)	HSE / Guidance
05	RR1082 - The effectiveness of HSE's regulatory approach: The construction example (HSE, 2016)	HSE / Guidance
06	RR834 - Preventing catastrophic events in construction Prepared by CIRIA and Loughborough University (Alan Gilbertson, Joseph G. Kappia, Lee S. Bosher, 2011)	HSE / Guidance
07	L24 - Workplace health, safety and welfare(HSE, 2013b)	HSE / Guidance
08	Reporting accidents and incidents at work (HSE, 2008)	HSE / Guidance
09	L153 - Managing health and safety in construction (HSE, 2015a)	HSE / Guidance
10	INDG275 - Plan, Do, Check, Act: An introduction to managing for health and safety (HSE, 2013a)	HSE / Guidance
11	HSG65 - Managing for health and safety (Health and Safety Executive, 2013)	HSE / Guidance

4.1.5.3. Questionnaire

Questionnaires are regularly used tools for acquiring survey data, which is generally numerical and easy to analyse (Dörnyei and Taguchi, 2009). Questionnaire surveys are usually used for quantitative studies to gather data from a specific set of participants to develop a piece of information or a theory. With appropriate planning, questionnaires may provide high-quality useful data, obtain high response rates, and enable anonymity, the latter promoting more honest and forthright responses than, say, interviews (Marshall, 2005). Moreover, it enables the researchers to design the questions in several ways to facilitate the research analysis; e.g. open questions, closed questions, quantity questions, categories questions, and raking/scaling questions. similarly, Marshall (2005) suggested that a questionnaire should avoid hypothetical, imprecise, ambiguous and assuming questions. Hence, the questionnaire will undoubtedly play an important role in collecting comprehensive data sets that can be easily compared, for instance, by region, age, and gender (Saunders, Lewis and Thornhill, 2013).

However, while conducting questionnaire special considerations should be given to questionnaire design, approaching the targeted audience, familiarity with a targeted audience, distribution strategy, and response time to ensure that participants have enough time to reply to the questionnaire (Marshall, 2005; Creswell, 2009; Alan Bryman, 2012; Saunders, Lewis and Thornhill, 2013). Moreover, based on the question types Cohen, Manion and Morrison (2020) categorized the questionnaire into structured, semi-structured and unstructured questionnaires. Marshall (2005) stated that a questionnaire should be written in user-friendly wording and language bearing in mind the targeted audience to make sure it is not misunderstood. Similarly, a polite and appropriate invitation must be sent to the participants for the engagement (Saunders, Lewis and Thornhill, 2013). This study has conducted a semi-structured questionnaire as the main research instrument to explore the research problem and propose a framework for managing the utmost factor affecting health and safety in the construction industry. The detailed commentary on questionnaire development, participants sampling, distribution and collection has been discussed in section-4.3.2.

4.1.5.4. Interviews

One of the popular strategy used for data collection in business and management studies are interviews (Saunders, Lewis and Thornhill, 2013). Kvale (2011) described an interview as a conversation between two persons that has a specific structure and purpose determined by the interviewer. Alan Bryman (2012) classified interviews as structured, semi-structured and unstructured. Similarly, Robert K. Yin (2014) grouped interviews into structured, focus groups and in-depth inquiries. Contrarily, semi-structured or unstructured interviews are considered a qualitative research strategy (Alan Bryman, 2012). In semi-structured interviews, the interviewer follows a line of inquiry but also allows the interviewees the flexibility to respond freely to the interviewer's queries. The interviewer carefully prepares a list of questions based on the research, however, some questions are open-ended and allow the researcher to ask follow-up questions.

Unstructured interviews also known as in-depth interviews, are described as the conversations between the researcher and respondent held with a purpose in mind or a line of a query to gather information about the research questions. However, in the unstructured interviews, there is no guideline or prepared questions to follow, rather, participants are approached ethically to gather as much information as possible. According to various authors, interviews are conversations in which the interviewer pursues a specific line of inquiry and can be performed in a variety of ways (e.g. Skype, face-to-face, email or telephone) (Creswell, 2009; Alan Bryman, 2012; Saunders, Lewis and Thornhill, 2013). For this research, semi-structured interviews have been selected for the framework validation to strengthen the reliability of research findings which has been discussed in section-4.3.3.

4.2. Adopted Research Methodology Rationale

Section 4.1 examined the methodological choices mentioned in the research onion developed by (Saunders, Lewis and Thornhill, 2013). Each layer of the research onion has been critically analysed and an appropriate selection has been made in the previous selection shown in Figure 4.6. A mixed-method approach has been adopted for this study considering the research objectives, strengths and weaknesses and philosophical positioning. Furthermore, this methodology has been adopted based on the onion research methodology proposed by Saunders, Lewis and Thornhill (2013) where each layer defines a philosophical dimension of this research. This is deemed the most appropriate methodology for this study as it allows the researcher to explore and interpret subjective knowledge in their social setting.

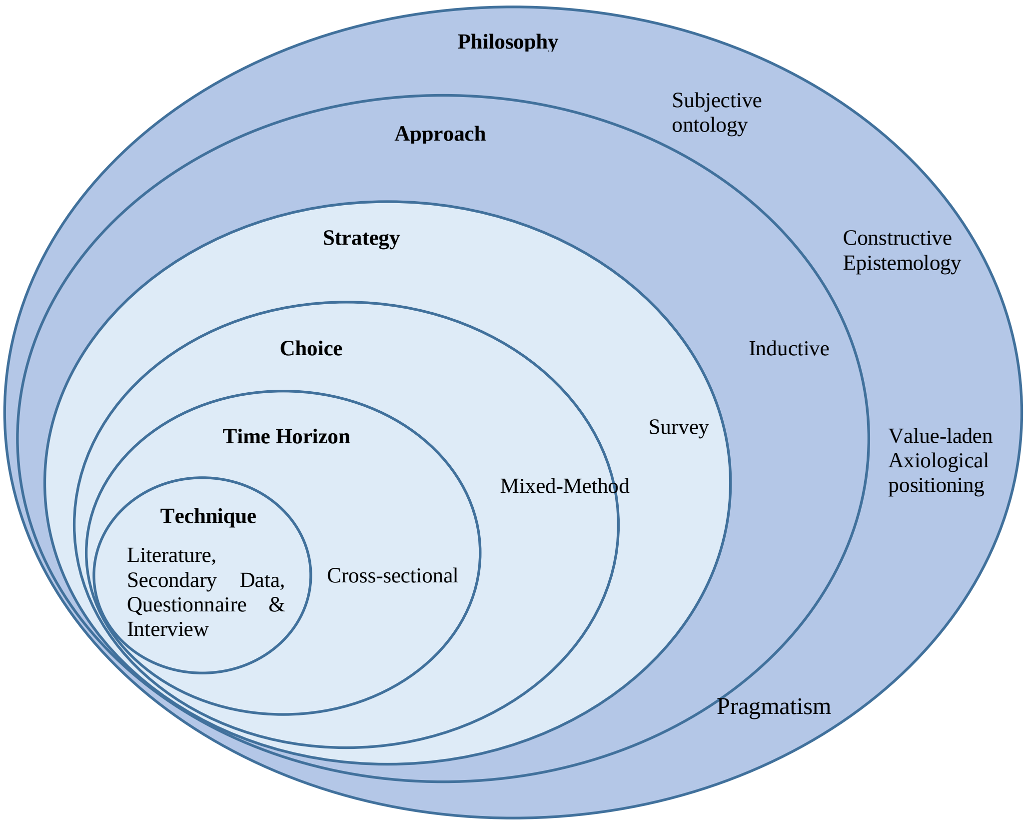

Figure 4.6: Adopted Research Methodology

Moreover, the adopted methodology has been selected based on the following reasons;

- The study seeks to explore the causes of accidents in the construction industry to identify the remedial measures to help eliminate those factors. The basic understanding has been developed through a literature review, however, for extensive insight into the issue, the construction H&S professionals within the UK must be engaged with reasonable sample size. As this research targeted a very specific audience therefore 47 participants were considered a reasonable sample size (Budiu and Moran, 2021). This was only applicable under the chosen research methodology for the appropriate research findings.
- The research explored the current safety practices as well as their weaknesses and strengths to develop a novel framework to improve safety management. This was only applicable by developing enriched data on the research queries to develop a framework based on that. Therefore, a questionnaire has been selected as the research instrument to approach the H&S professional within the UK construction industry.
- The data gathered from the questionnaire had been analysed quantitively for further research and framework development. This was followed by semi-structured interviews to validate the research findings by engaging the top-ranked construction H&S professionals as well as the HSE personnel. hence, the mixed method has been the most appropriate approach for this study given the research type, limitations and available options.

4.3. Research Process

The previous two sections in this chapter inspected the research philosophical positioning, approaches, strategies, choice, time-horizon, techniques and adopted research methodology. However, this section will demonstrate the research process and steps involved in carrying out the research. This comprises carrying out the essential steps to answer the research questions and develop research findings. Therefore, the research process is carried out in four key stages.

The first stage explores the research issues as well as develops an understanding of the research problem and examines the existing remedial practices. Followed by the second phase; which develops a research instrument based on the findings of the first phase and the carry out of data collection. Whilst the third phase involves data analysis and framework development based on the research findings, and lastly, the last research objective of validating the framework has been carried out in this phase by conducting semi-structured interviews. These four phases have been achieved to develop the framework which has been described in the next sections (Figure 4.7);

1) Literature review (Ch 2&3)
2) Questionnaire Survey (Ch 5)
3) Framework Development (Ch 5)
4) Research Validation (Ch 6)

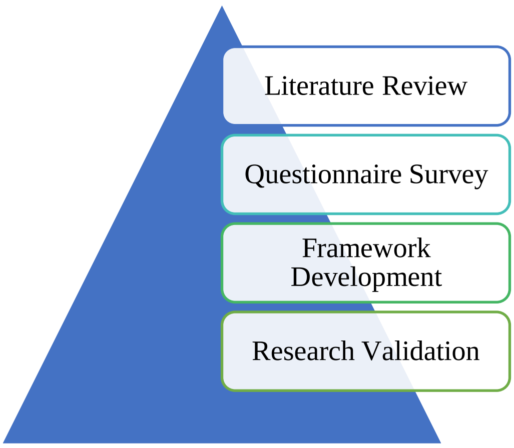

Figure 4.7: Research Process

4.3.1. Step 1: Literature Review

As mentioned in section 4.1.7, the literature review has been the most critical and vital part of this study. It enabled this study to review and understand the existing knowledge on H&S practices, weaknesses, and the factors affecting safety in the construction industry. Moreover, it built the foundation for this study by identifying the research gaps as well as helping compile the research questions. The literature review for this study has been carried out in two chapters. Chapter 2 examined the overview of health and safety in the construction, performance, H&S systems and regulations as well as using a specially designed systematic approach to explore the factors affecting H&S. However, Chapter 3 presents a comprehensive insight into the human factor, accident causation models, human reliability analysis and examined immersive technologies which could help to develop an immersive framework for H&S management. Moreover, objectives one, two and three have been achieved through a literature review, whilst the rest of the research objectives were also achieved based on the literature study. Figure 4.8 below illustrates the literature review sequence by chapter.

The literature review has been carried out through a systematic literature review process described by (Kitchenham and Charters, 2007). This is typically used when there is little evidence or when the research area is too broad during the initial study. Hence, the literature review started with finding the state-of-the-art literature on accident causation in the construction industry, its impacts on the industry's performance, and current safety management systems to find the research gap in the literature. This was carried out by selecting the appropriate databases such as; Google Scholar, conference proceedings, Health and Safety Executive (HSE) reports (Secondary Data) and Nottingham Trent University (NTU) database. This developed a comprehensive knowledge of the research problem and facilitated the carrying out of further research based on the literature review.

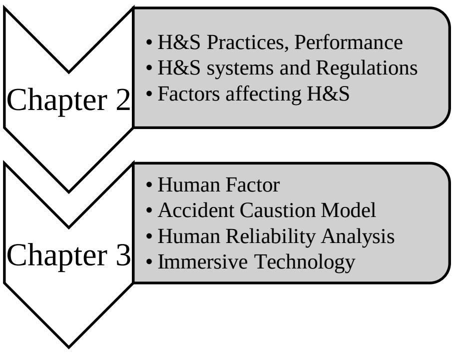

Figure 4.8: Flowchart of Literature-review Chapters

4.3.2. Step 2: Questionnaire Survey

The questionnaire study conducted in this research targeted the construction H&S professionals to seek their understanding of the research questions as well as explore their knowledge of accident causation, factors affecting the H&S, human reliability analysis (HRA) and their feedback on the application of immersive technology to eliminate the causal factors. An online semi-structured questionnaire for health and safety professionals was developed in three sections to gather participants' views on the causes of the accident and human reliability assessment. The conducted questionnaire has acquired significant knowledge on the health and safety issues, practices used in the industry and a detailed understating of mitigating the issues based on the participant's knowledge.

The questionnaire has been developed in three sections to make it understandable and user-friendly for the participants. To ensure the quality as well as the integrity of the research, the first section inquired the participants for general information about their expertise, job role, age, and health and safety. Whilst section two of the questionnaire developed the knowledge of accident causation according to participants' knowledge and experience, whereas section three seeks their understanding of human factor management using immersive technology. Overall thirty-four (34) questions have been asked to the participants. A total of 47 questionnaires were sent to the targeted audience with a response rate of 72%. Moreover, a non-probability sampling technique has been used for the questionnaire distribution followed by the quantitative analysis. Furthermore, the questionnaire has been designed with different types of questions for the best outcome and to facilitate the data analysis. This includes open-ended multiple-choice questions, grid questions and scaling/ranking questions. The developed questionnaire has been attached to the Appendix-I of this document.

4.3.2.1. Data Sampling

Data sampling is one of the vital parts of any research especially if it involves social constructivism. Saunders, Lewis and Thornhill (2013) argued that a researcher much considers sampling irrespective of the research objectives and questions to choose an appropriate sample for the research. Sampling is the technique of choosing the right units from the population that can contribute to the research outcomes (Saunders, Lewis and Thornhill, 2013). Furthermore, Saunders, Lewis and Thornhill (2013) mentioned two types of sampling techniques; (i) probability sampling, and (ii) non-probability sampling. In the first technique, the unit population is selected based on some level of randomness. However, in the latter type, a unit population is usually selected based on the subjective judgment of the researcher rather than random selection.

This research has been conducted on a real-time issue specifically in the construction industry, therefore, the non-probability purposive sampling technique has been selected. Moreover, this study aimed to explore accident causes and shortcomings of the current H&S practices related to the UK construction industry. Therefore the sample population selected for the questionnaire survey were H&S professionals in construction with reasonable experience in the industry. Hence the people selected for this study were H&S managers, directors and H&S leaders. Moreover, to ensure the research validity and integrity, it has been made sure that the selected sample must have H&S certification for the best possible findings.

4.3.2.2. Data Analysis & Research Findings

Data analysis is another significant component of any research since it allows you to analyse the acquired data and develop conclusions from it (Creswell, 2009). It begins with the breakdown, separation, or disassembly of research materials into parts, pieces, elements, or units. Moreover, the researchers often combine quantitative and qualitative data to classify them, find types, sequences, or patterns and find evidence to address the research's initial assumptions (Robert K. Yin, 2014). Saunders, Lewis and Thornhill (2013) mentioned two types of quantitative data analysis techniques 'descriptive' and 'inferential'. Descriptive statistics are used to describe the central trend of the data as well as determine the dispersion of the data from the central trend. However, inferential analysis examines data beyond central trends and is used to examine relationships, differences, and trends in numerical data. The inferential analysis allows the data to be examined for the strength and significance of the variable's correlations (Saunders, Lewis and Thornhill, 2013).

On the successful completion of the questionnaire survey, this study carried out quantitative data analysis of the gathered empirical evidence. The quantitative analysis of the research is aimed at validating the literature review research findings as well as seeking knowledge to develop a framework which has later been validated using semi-structured interviews at a later stage. Description quantitative analysis technique is used for this study to analyse each question as well as the central tendency. Each question has been analysed and graphically represented in terms of graphs, bar charts and scale charts. Moreover, a detailed discussion has also been presented along with the graphic representations to examine the research findings in context with the research questions. Afterwards, the central trend has been analysed for the development of the framework

4.3.3. Step 3: Framework Development

The proposed framework was developed in two stages. Firstly, based on the in-depth literature review carried out on the H&S factors, an initial framework was developed to conceptualize the management of identified H&S factors. This framework highlighted the prominent factors affecting safety management as well as further refine the research findings which helped the research to develop the questionnaire. Afterwards, a questionnaire study was conducted and the findings have been incorporated to propose the final H&S framework.

4.3.3.1. Initial Framework

The study entailed a systematic literature review as a research methodology to explore the factors causing H&S management issues in the construction industry among the peer-reviewed articles and develop an initial SMS framework mitigating all factors. The review was performed by selecting articles from notable journals and conference proceedings that have been used extensively by researchers and practitioners in the area based on the specific search criterion. The systematic research methodology used has been shown in Figure 4.9 below.

The selection of publications was the initial phase in the review process, and 295 articles were selected from peer-reviewed databases namely; Science Direct, Emerald, Taylors & Francis, ASCE, and some IOP publications. The selection criteria are based on specific search keywords relating to study goals and publication dates. The search strings used were; (1) Health and safety factors in construction, (2) Accident causal factors in construction, (3) Factors influencing/affecting H&S Management in construction, and (4) Factors causing poor Occupational health and safety (OHS) management, and (5) Factors influencing safety performance. Secondly, no article older than 2005 was chosen as part of the research, which attempted to examine papers from the previous 15 years to provide insight into the most recent safety concerns. As a result, the papers were chosen during the review process based on the title, year of publication, and keywords. A detailed analysis of the systematic literature review and development of the initial framework has been provided in chapter 2.

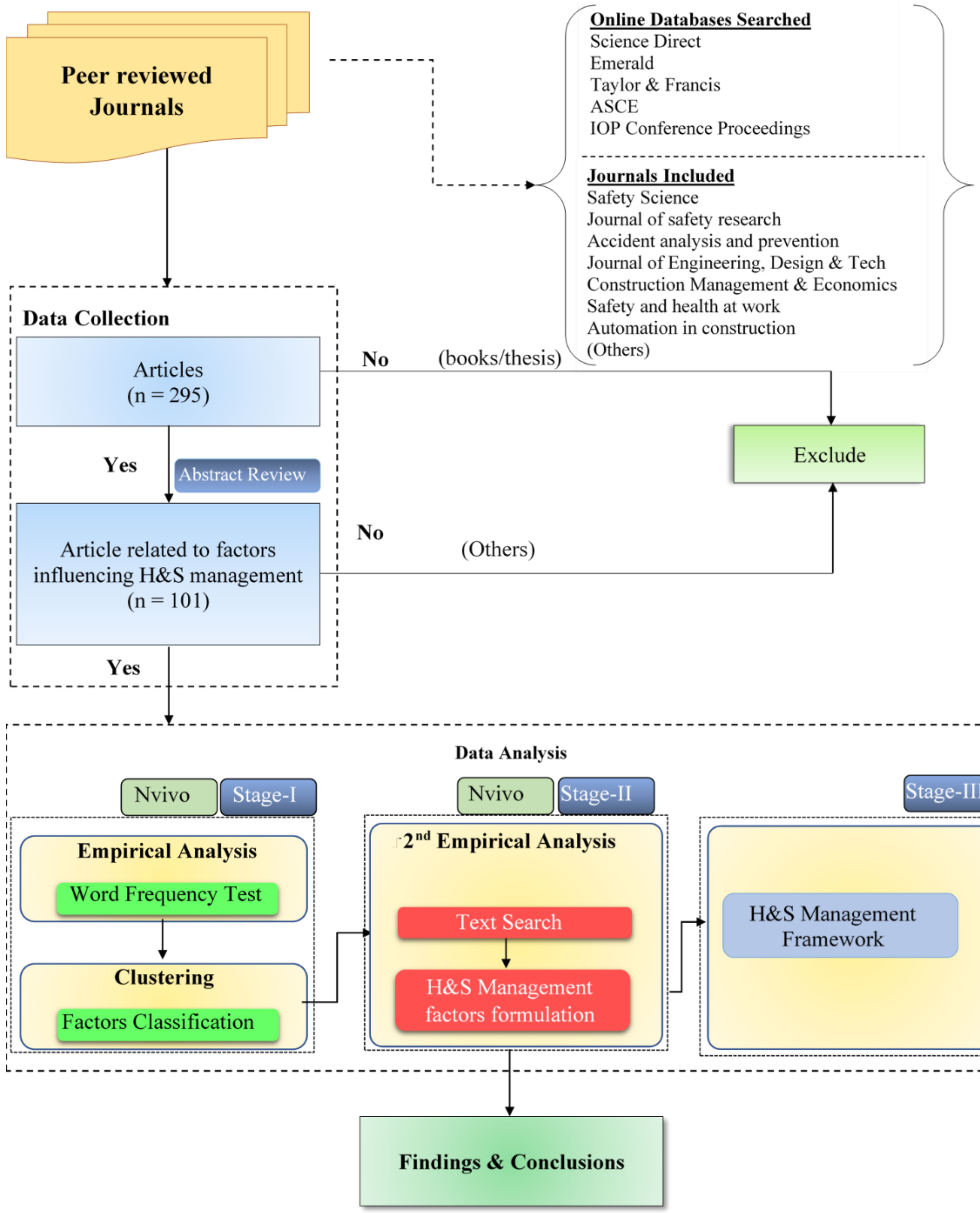

Figure 4.9: Methodology for Systematic Literature Study

4.3.3.1. Literature Selection

An in-depth search has been carried out to locate the articles related to the factors in H&S management within the construction industry. The downloaded literature has been through the screening process to outline the most suitable articles associated with the research objectives. For that purpose, the abstract review has been conducted for all 295 papers and a total of 106 papers specific to H&S management factors were shortlisted for the empirical analysis. The articles have been categorised by the year of publication and type of publication as shown below.

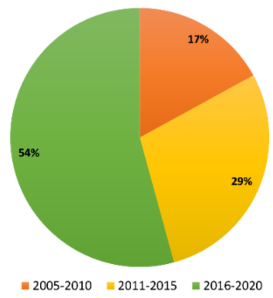

Figure 4.10: Literature Classification by Year of Publication

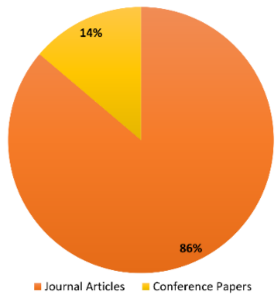

Figure 4.11: Literature Classification by type of Article

Out of the selected articles, 54% of them ranged between the past five years as shown in Figure 4.10. Moreover, for the review analysis, only journal and conference papers were selected, and no books or a thesis were included in the research to evaluate the most adequate peer-reviewed knowledge. Subsequently, 86% of the chosen articles were mostly journal publications and 14% were conference proceedings as indicated in Figure 4.11. The sources of the journal articles and conference proceedings are listed in Table 4.5.

Table 4.5: List of Journals

Journals	No# of Papers
Safety Science	17
International Journal of Occupational Safety and Ergonomics	8
Construction Management and Economics	5
Engineering	5
IOP Conference Series: Earth and Environmental Science	5
Journal of Engineering	5
IOP Conference Series: Materials Science and Engineering	4
Journal of Construction Engineering and Management	4
Journal of Safety Research	4
International Journal of Project Management	3
Procedia - Social and Behavioural Sciences	3
Accident Analysis and Prevention	3
Association of Researchers in Construction Management	2
Automation in Construction	2
Journal of Management in Engineering	2
5th International Project and Construction Management Conference (IPCMC 2018)	1
Advances in Civil Engineering	1
American Journal of Engineering Research	1
Applied Ergonomics	1
Australasian Journal of Construction Economics and Building	1
Automation in Construction	1
Benchmarking	1
Built Environment Project and Asset Management	1
Construction Economics and Building	1
Construction Innovation	1
Data in Brief	1
Human and Ecological Risk Assessment	1
IFAC-Papers Online	1
International Journal of Environmental Research and Public Health	1
International Journal of Industrial Ergonomics	1
International Journal of Managing Projects in Business	1
International Journal of Occupational Hygiene	1
International Journal of Productivity and Performance Management	1
International Review of Management and Marketing	1
IOP Conference Series: Earth and Environmental Science PAPER	1
IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE)	1
Journal of Building Engineering	1
Journal of Civil Engineering and Management	1
Journal of Construction in Developing Countries	1
Journal of Physics: Conference Series	1
MANAS Journal of Engineering	1
Policy and Practice in Health and Safety	1
Safety and Health at Work	1
Safety officers and workers were asked to indicate how effective	1
Total Quality Management and Business Excellence	1
World Journal of Science	1
Journal of Financial Management of Property and Construction	1

4.3.3.2. Proposed Framework Development

The designed framework is based on the research findings of an extensive literature review and the questionnaire survey targeting construction safety practitioners. The process of developing the framework has been explicitly discussed in Chapter 5. That involves the identification of the root causes of accidents in the construction industry, exploring the shortcomings of existing safety practices in the construction industry and reviewing the potential technologies to improve the shortcomings through a comprehensive literature review and pilot study. Moreover, based on the research findings of the first two steps of the research process this research proposed a framework utilizing immersive technology. For this study, the framework was determined to be the best choice for representing the safety management system while taking into account underlying elements and establishing the relationship between accident causes. Furthermore, the framework would assist construction experts in assessing potential flaws in the current system as well as highlighting the critical processes required for safety management. Furthermore, the following criteria were used in the selection:

1. The framework's capabilities will extend beyond descriptions of "what" to explanations of "why" and "how," allowing clients to understand why they need a framework for effective safety management.
2. With the main goal of identifying the relationship between errors and probable accidents, the proposed framework will emphasise the relationship between multiple variables producing an accident on site.
3. Develop a systematic method to remove accident causes based on theoretical discoveries as well as practical investigation.
4. The proposed framework will give H&S practitioners insight into the safety process, allowing them to utilise a practical approach to manage the major issues that affect health and safety.

A detailed discussion on the development of the immersive H&S framework has been carried out in chapter 5.

4.3.3.2.1. Framework Development Process

Prior to beginning data collecting and analysis, the research methodology emphasises the significance of conceptualising the phenomena under study or pre-establishing an initial theory. When conceptualizing a phenomenon, it is possible to identify the main theories relevant to the study, how it is constructed, and the circumstances in which these theories and relationships are believed to be true (Robert K., 2014). Furthermore, the initial data collection involving the questionnaire provides rigorous insight into the research questions and interrelationships required for the development of the framework. When researching to examine a specific intended or present procedure or problem, the technique might be defined primarily by two fundamental concepts: the framework and the model (Gartner, 1985; Greene, Caracelli and Graham, 1989). Miles and A. Michael Huberman (1984) defined the framework as the most recent version of the researcher's map of the area under investigation. Gartner (1985) differentiating framework and the model argued that the framework establishes the overall structure of the study, whereas the model delves into the specific methodology. Similarly, Robert K. Yin (2014) mentioned that frameworks are used in research to provide a general picture of a possible course of action or to suggest a preferred approach to a thought or idea.

The researchers have proposed three distinctive types of frameworks; ‘conceptual’, ‘theoretical’, and ‘practical’ frameworks (Gartner, 1985; Eisenhardt, 1991). Miles and A. Michael Huberman (1984) defined the conceptual framework as a graphical or textual product that "describes, either visually or narratively, the essential objects to be researched, the key aspects, ideas, or variables, and the hypothesised relations between them. More precisely, a conceptual framework presents the occurrence of a phenomenon and establishes the relationships between the related variables and overall aspects of research (Leshem and

Trafford, 2007). Moreover, Imenda (2014) mentioned that the conceptual framework represents an "integrated" view of looking into a problem. From their point of view, it is evident that the conceptual framework may evolve as research progresses. A practical framework, on the other hand, presents the practicality of the problem under examination based on theoretical explanations. Eisenhardt (1991) suggested that the ‘practical framework’ guides the researchers to identify what works in the exercise or experience of doing something by the people directly involved in it. However, the theoretical framework is usually based on a theory to explain the process. Imenda (2014) refers to the theory or set of concepts that researchers choose to guide their research. Therefore, a theoretical framework is the use of a theory or a group of concepts taken from a theory to explain an occurrence or focus attention on specific phenomena or research challenges.

For this research, the practical framework has been found as the most appropriate selection to represent the safety management system taking into account underlying factors and proposing a practical solution. Moreover, the practical framework would help construction professionals identify the potential weakness in the contemporary safety system as well as highlight the essential steps required for safety management. Moreover, the selection has been made on the following;

1. The practical framework's ability will go beyond descriptions of 'what' to explanations of 'why' and 'how,' providing an answer as to why clients require a practical framework for robust safety management.
2. The practical framework will emphasize the relationship between different variables causing an accident on site with the main aim to manage human factors in the construction industry.
3. Based on the theoretical findings as well as the quantitative research develop a systematic approach to eliminating causal factors of accidents.

4. The framework will provide insight into the safety process to facilitate H&S practitioners using a practical solution to manage the substantial factors affecting health and safety.

Based on the above arguments and literature, the practical framework opted as the most appropriate selection to shape the theoretical and empirical findings into the safety management method. Figure 4.12 illustrates the framework development process used in this study.

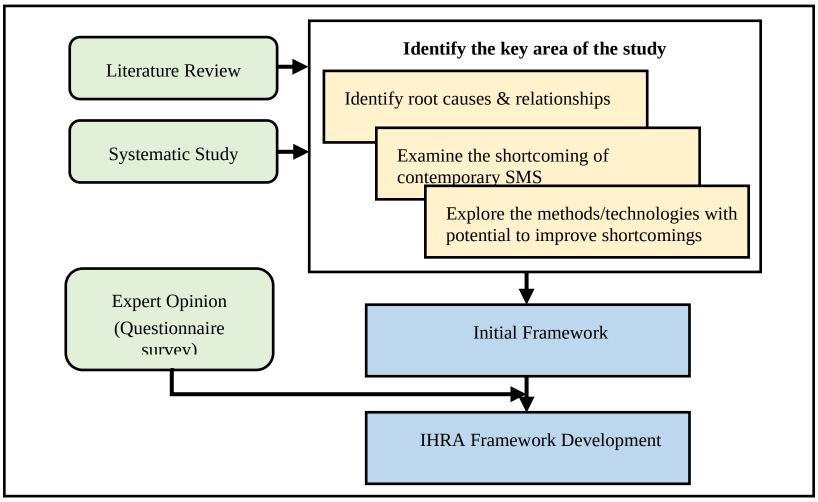

Figure 4.12:Framework Development Process

4.3.4. Step-4: Research Validation

On the successful development of the framework, the succeeding objective of this study was to validate the framework. This has been achieved by carrying out semi-structured interviews with safety experts in the construction industry. The qualitative study conducted validated the suggested H&S framework and provided notable results on H&S management in the construction industry from which some implications can be drawn which has been discussed in Chapter 6. Non-probability sample technique has been used targeting lead safety professionals within the UK construction industry with a total of twenty (20) participants. Interpretative Phenomenological Analysis (IPA) has been identified as an appropriate method for analysing semi-structured interviews. Each study objective has been validated essentially to validate the development of the suggested framework. A detailed discussion of research validations has been carried out in Chapter 6 of this thesis.

4.3.4.1. Interpretative Phenomenological Analysis (IPA)

Interpretative phenomenological analysis (IPA) has been a recently developed qualitative data analysis approach and has been frequently used in psychology, medical sciences and social studies since its inception by Jonathan Smith (Smith, 2004; Biggerstaff and Thompson, 2008). It enables the researcher to conduct a rigorous investigation of subjective experiences and, in particular, social cognitions (Biggerstaff and Thompson, 2008). The goal of interpretive phenomenological analysis (IPA) is to learn more about how people make sense of their own personal and social worlds. IPA has become the dominant technique for qualitative data analysis in several academic fields (Tuffour, 2017). Moreover, IPA has a theoretical underpinning with phenomenology, hermeneutics (interpretation) and idiography (interactionism) (Smith, 2004, 2011; Palmer *et al.*, 2010). Phenomenology is focused on the study of lived human experiences as well as the study of how perceived and appear to the consciousness (Tuffour, 2017). Hermeneutics deals with interpreting the participant's conception of the subject or event under consideration. Researchers believe that IPA involved double-hermeneutics; thus two stages of interpretation (Smith, 2004, 2011; Palmer *et al.*, 2010). The participants are attempting to make sense of their experience/world, while the researcher is attempting to understand the participants' attempts to make sense of their experience/world (Hefferon and Gil-Rodriguez, 2011). Hence, IPA is intellectually linked to hermeneutics and interpretational theories. Similarly, IPA has its roots in idiography which deals with the commitment to analyse each case in a corpus in detail. Starting with a careful assessment of one case until some degree of closure or conclusion is obtained, IPA moves on to a deep analysis of the next case, and so on through the corpus of cases (Smith, 2004).

Nevertheless, IPA believes in the person as a cognitive, linguistic, social, and physical being, and implies a chain of links between people's speech and their thinking and emotions. Moreover, IPA provides a flexible and adaptable method for comprehending people's experiences. The difference between IPA and description qualitative analysis is the methodology involved in the IPS process. IPA is carried out in several stages to critically and rigorously interpret participants' experiences. Therefore, this research selected IPA as the most appropriate analysis technique to analyse lived experience of construction professionals in the knowledge through a rigorous process of interpretation and interaction. The stages involved in interpretation phenomenological analysis (IPA) are;

i. Stage 1: first interaction with the text
ii. Stage 2: identification of preliminary themes
iii. Stage 3: grouping and clustering the emerging themes
iv. Stage 4: summarizing the findings

The most often used research instrument in IPA is semi-structured interviews which have also been practised for this research. Following the interviews, each interview recording is meticulously transcribed, often incorporating signs of pauses, mishearing, and apparent mistakes if they are noteworthy. The interview transcripts are then compared to the original recordings, which may or may not correspond to those listed on the researcher's prompt sheet. On the successful completion of interview transcripts, stage 1 of the IPA analysis begins. Based on the rigorous analysis methodology used in the IPA to interpret qualitative data, this research has utilized IPA for the analysis of semi-structured interviews conducted for the validation of this study.

4.3.4.1.1. Stage 1: First Interaction with Text

Close reading and re-reading of the interview text is key to IPA analysis (Smith, 2011). In IPA analysis, while reading the transcript or other text, the researcher takes notes on any thoughts, observations, or insights that come to mind. Any repeating phrases, the researcher's concerns, emotions, and descriptions of or comments on the language used are likely to be included in such notes. Notes are utilised at this step to document points that the researcher notices while reading the text. It's customary to jot down these early thoughts in one of the transcript's margins (Smith, 2004; Palmer *et al.*, 2010; Tuffour, 2017). In most of the analysis techniques, the researcher tries to suspend preconceptions and judgments when reading the text to focus on what is offered in the transcript data (Biggerstaff and Thompson, 2008). This concept is called ‘bracketing’ which entails a temporary refusal of critique, which would bring in the researcher's preconceptions and experience, as well as a suspension of critical judgement. However, the IPA recognises the need for interpretation, the concept of ‘bracketing’ is therefore controversial in IPA and, in any case, gives way to a more interpretive process as the analysis progresses. This study used MS Teams for the interviews and the interviews were then cautiously transcribed to a word document. Using the IPA stage-1 methods, the transcripts were thoroughly examined and observations and emergent concepts were written down for further research.

4.3.4.1.2. Stage 2: Identification of Preliminary Themes

At this stage, the researcher goes on to re-read the transcript and choose themes that best express the important characteristics of that particular interview. The researcher usually looks for potential or plausible relationships between topics when identifying emerging themes from each portion of the transcript (Smith, 2004; Palmer *et al.*, 2010). Consequently, as with any qualitative study, the researcher may come across data that contradicts the emerging narrative. This is particularly obvious in the rare “disconfirmation event” in which the individual's narration or topic recognised in that perspective differs significantly from the majority of the other participants (Smith, Harré and Langenhove, 1995). Such dissonance will urge the scholar to go back over previous transcripts to see whether anything important was overlooked or misunderstood. Only then would the researcher introduce a contradictory or opposing idea. Following the IPA methodology, the written transcripts were rigorously examined and then emerging themes from each question have been underpinned. A detailed discussion of the emergent themes has been carried out in section 6.3.

4.3.4.1.3. Stage 3: Clustering the Emergent Themes

This is one of the most critical stages of IPA analysis to identify the emerging preliminary concepts from the transcripts and therefore describes the potential route toward further analysis. The stage-3 entails attempting to offer the study a general structure by grouping the emergent themes into ‘clusters’ or ‘concepts’. At this stage, the objective is to come up with a group of themes and find superordinate categories that indicate a hierarchical relation between clusters. The emerging themes have been developed for each of the research queries made during the interview and transcribed into the clusters to find the relationship between the clusters that emerged from the clustering of all the participant's transcripts.

4.3.4.1.4. Stage 4: Summarising the Research Findings

Stage 4 is to create a master list of clusters identified in the previous stage, sometimes known as a table. It's critical to organise these themes into a framework that recognises the major characteristics and concerns raised by the research participant. These are frequently presented as a table with data from the interview and a quotation that the analyst believes best represents the essence of the person's thoughts and emotions concerning the topic under investigation. This stage has also been practised for this research to summarise as well as evaluate the findings from the defined clusters out on the participant's feedback.

4.4. Validity & Reliability of Quantitative and Qualitative Research

The goal of the qualitative and quantitative paradigms is the same: to discover the ‘truth’. The concerns of reliability and validity have been extensively discussed by advocates of both quantitative and qualitative researchers to evaluate the research quality. Reliability is the degree to which results are constant over time and a precise representation of the entire population under study. A research instrument is deemed to be trustworthy if the study's findings can be replicated using a similar approach (Golafshani, 2003). On the other hand, Validity assesses how accurate the research findings are or whether the study measures what it set out to measure (Bashir, Afzal and Azeem, 2008). To test speculative generalisations, logical positivist or quantitative researchers use experimental techniques and quantitative metrics (Hoepfl, 1997). Subsequently, qualitative research findings are a different type of knowledge as one party argues from the underlying philosophical nature of each paradigm (Golafshani, 2003).

Despite the fact that the term "reliability" often refers to a concept used for testing or evaluating quantitative research, however, a good qualitative study can assist us in “understanding an otherwise enigmatic or confusing situation” (Creswell and Miller, 2000). To evaluate the credibility, consistency and authenticity of the research instruments both quantitative and qualitative research instruments have been passed through the reliability by conducting pilot studies. For this purpose, the instruments were sent to a small sample size including five participants from the selected audience and their feedback has been incorporated into the research instruments. For the research validity, the qualitative semi-structured interview questionnaire was designed to validate the framework as was as the research objectives. Moreover, the framework has been validated by showing the framework to the participants during the interviews. This methodology helped validate the research as well as the proposed framework. A detailed discussion on the research and framework validity has been conducted in Chapter 6 and each of the research objectives has been validated.

4.5. Chapter Summary

This chapter extensively reviewed and examined the available methodological choices as well as commented on the adopted methodology. First of all, the chapter began by demonstrating the philosophical assumptions that this research was based on. Each of the research philosophies, approaches and techniques were unfolded in pursuit to select the most appropriate methodology. The chapter then went on to describe several research paradigms, such as positivism and interpretivism, and why a qualitative research paradigm was the best fit for this investigation. This was due to the reasonable quality of the approaches that could achieve the outlined goals and objectives of this study. Additionally, the research paradigms and philosophies that affected the methodologies and methodology employed in this study were also discussed in this chapter. Following that, a thorough description of the study's steps was given, as well as a justification for the methodologies used. This indicates that the study was based on appropriate methodology, implying that the data presented in the study was credible. The chapter also went through each method and approach used, as well as how the study outcomes were recorded. Finally, the chapter detailed the steps done to improve the research data quality in terms of validity and reliability. The results of the exploratory investigation have been presented and discussed in the next chapter.

Chapter 5: Data Collection & Analysis

5. Introduction

The previous chapter presented a detailed commentary on the research methods and adopted research methodology. This chapter reviews the data collection and analysis of the questionnaire survey conducted in this research. The questionnaire used for this research will be analysed and based on the research findings, this chapter will propose a framework for health & safety management in the construction industry.

5.1. Survey Distribution

After selecting the right sample to carry out the survey the next phase in the research was to acquire the selected sample and distribute the questionnaire. As mentioned in section 4.3.2, an online questionnaire route has been selected for this research to approach the maximum number of participants as well as to facilitate the participants and data collection. Therefore, the research intended to approach as many participants as possible based on the designed sampling criterion using all the available resources. The selected sample participants were contacted through personal contacts, Linkedin contacts and with the help of a few construction organisations. Forty-seven questionnaires have been sent out to the H&S experts form where 34 responded at a response rate of around 72%. The respondent profiling has been carried out in the next section. The developed questionnaire has been attached to the Appendix-I of this document.

5.1.1. Demographic Information of the Respondents

For the robust evidence, the survey was sent to health and safety leadership and the people responsible for the safety planning of the construction and infrastructure projects who showcase knowledge, experience and leadership role in occupational health and safety management. the purpose of targeting this particular group of participants was to get a comprehensive perception and insight into H&S practices and issues as well as the factors affecting safety in the construction industry. In context to the responded survey, around 59%

of the respondents represented health and safety managers, 18% represented H&S leaders, and 14% represented H&S directors in the construction industry including a few others as shown in Figure 5.1.

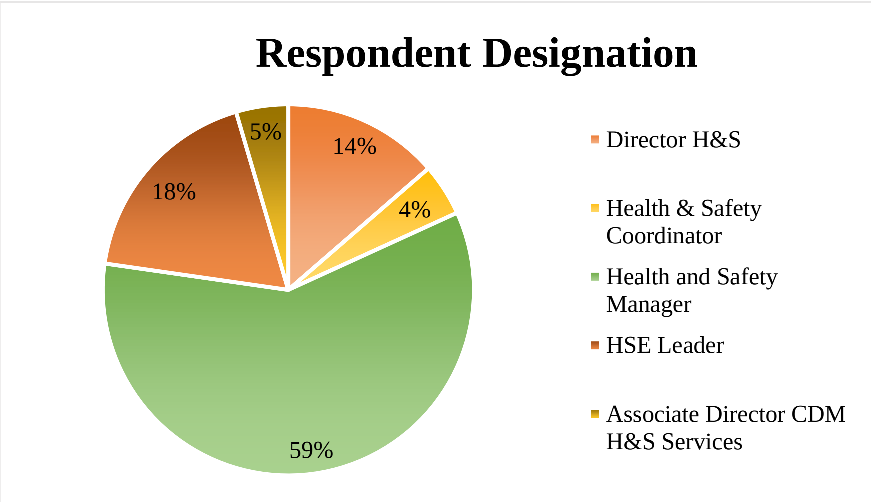

Figure 5.1: Respondent's Designation

Furthermore, for the vigorous research findings, participants were specified based on the H&S certification. Almost all of the respondents had H&S certification from reputed organisations and have shown the required knowledge and skills to work as H&S lead in construction projects. Amongst these respondents, 32% had construction safety certification NEBOSH (National Examination Board in Occupational Safety and Health), 23% were entitled to CMIOSH certification, and 18% had GradIOSH. Similarly, other respondents were also H&S-certified professionals as shown in Figure 5.2. Acronyms for all H&S certifications have been listed in Table 5.1. Subsequently, all of the respondents demonstrated significant experience in construction and infrastructure project.

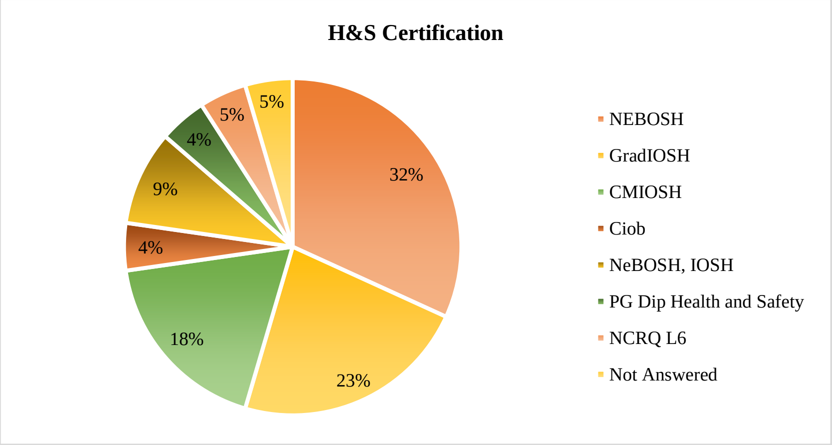

Figure 5.2: H&S Certification Represented by Respondents

Table 5.1: H&S Certification Acronyms

H&S Certification	Acronym
NEBOSH	National Examination Board in Occupational Safety and Health
GradIOSH	Graduate Member - Institution of Occupational Safety and Health
CMIOSH	Chartered Member - Institution of Occupational Safety and Health
CIOB	Chartered Institute of Building
NCRQ	National Compliance and Risk Qualifications
PG Dip Health & Safety	Post Graduate Diploma in Health & Safety

The targeted organisations have also been put through the screening process to get the right audience for the questionnaire survey. The purpose of the screening was to identify organisations that have pragmatic safety management systems to deal with safety risks. This helped to develop the essence of inclusiveness and emphasis on the right audience for the selected objectives. For said purpose, the respondents were investigated about the safety policies, safety management systems, safety culture and other safety management measures in their organisations. A set of multiple-choice questions on a scale of "Yes", "No" and "Not Sure" has been asked to the respondents and as aimed by the research, all the targeted organisations/companies fulfilled the required criteria of distinctive safety standards. Survey results have shown that all of the companies comply sufficiently with the expected safety system in the organisation. It has been found that 100% of the targeted companies had a safety management department, and safety policy and carry out a risk assessment and safety inspections for safety management of the construction projects. Similarly, 95% of the companies hold a comprehensive safety management system including the safety training of their employees working on the construction site. Other measures included in this section are shown in Figure 5.3.

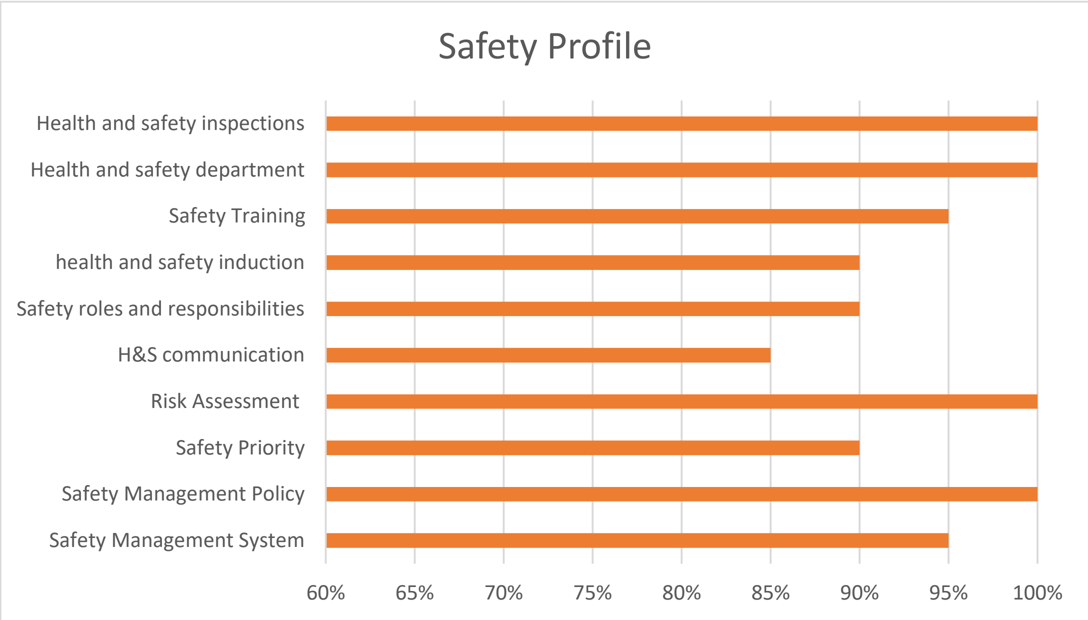

Figure 5.3: Targeted Companies Demographics

5.1.2. Research Findings on Accident Causation

The systematic literature review research revealed vigorous insight into the health and safety representative's perception of accident causation as well as safety management. As explored in the literature, safety professionals redeem the same opinion on accident causations highlighting the severity of human actions behind the accidents on construction sites. Almost all of the participants highlighted human error as the main cause of incidents in construction. that validated the initial research finding through a literature review. The participants have been enquired about the causes of accidents on the construction sites in section II of the questionnaire. Several questions have been asked about the causes of accidents and prevention techniques used in the construction industry to get a robust intuition of safety management in the industry. Validating the literature review, 60% of the participants mandated human error as the root cause of accidents on construction sites. Another prominent cause of accidents found was system complexity which contributes significantly to the human shown in Figure 5.4.

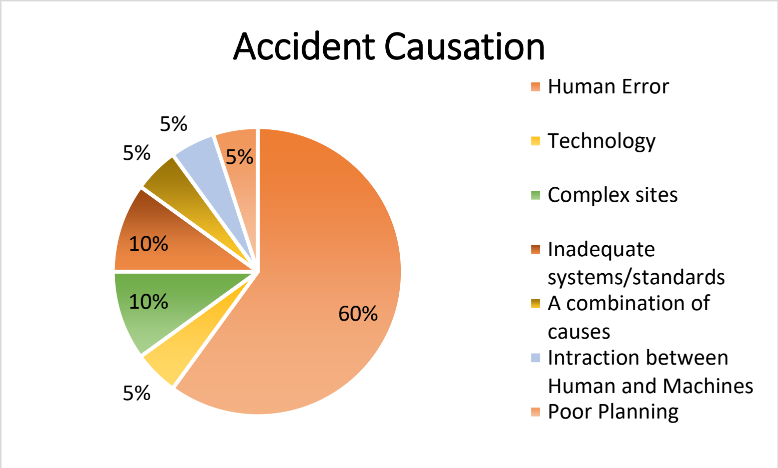

Figure 5.4: Respondent's Perception of Accident Causation

A literature review revealed that leadership has a significant role in safety management in terms of developing safety policies, and practices as well as promoting a safety culture in the organisation (Fang, Chen and Wong, 2006b; Khdair, 2011b; Ametepey, Aigbavboa and Ansah, 2015; Zhou, Goh and Li, 2015). Consequently, the lack of leadership attention to safety could inevitably cause an accident on the construction sites. This quantitative study also sought the respondent's views on accident responsibility in the construction organisation to decode the accident mechanism. Therefore, a series of questions to evaluate the accident responsibility of people responsible for H&S at different levels of organisational hierarchy. The research revealed that top management shares more responsibility to manage as well as regulate safety during the construction phase as found in the literature. It has been stated by 48% of the respondents that leadership carry a vital role in making sure that H&S is managed well throughout the construction projects. Figure 5.5 illustrates the respondent's view on accident causation responsibility. Moreover, it has also been inquired 'how' leadership causes an accident on the construction sites and respondents have revealed that 'lack of safety awareness and 'improper risk perception' are the most significant causes of accidents initiated by the leadership. More causes of accident due to leadership is illustrated in Figure 5.6.

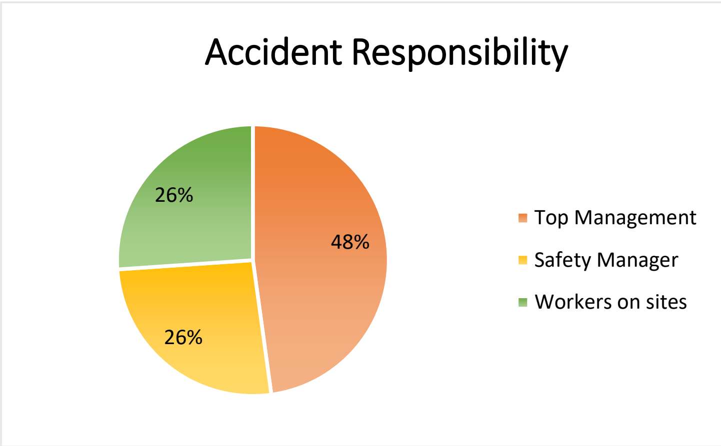

Figure 5.5: Respondent's Views of Accident Causation

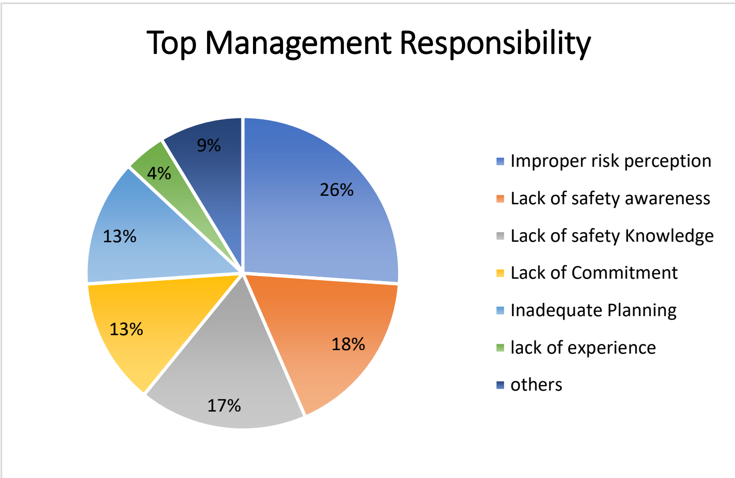

Figure 5.6: Responsibility of Leadership for Accidents

However, a few intriguing facts have been highlighted by the H&S representative regarding the root causes of human errors in the complex socio-technical system. The key reason behind human error has also been inquired in a question to analyse/elaborate on the human error mechanism. Unsafe actions have been found as the significant reason behind the accident with a vantage of around 39%, miss-communication has been ranked as the second and lack of training was the third main reason for the accident on construction sites shown in Figure 5.7. Subsequently, the reason behind the unsafe actions was found as inappropriate behaviour to a great extent. Inappropriate behaviour counted 29%, attitude 25% and lack of training counted 22% as a reason behind the unsafe actions. Similarly, other reasons to execute the error of commission are shown in Figure 5.8. Therefore, according to the construction H&S professional, human error affects the whole safety system not only the workers on site.

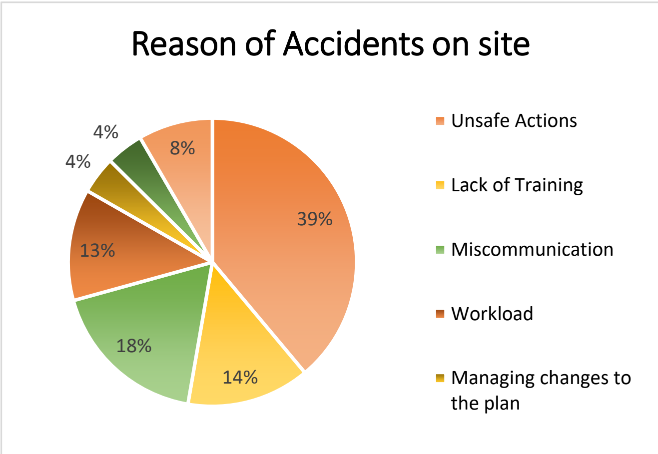

Figure 5.7: Causes Of Accidents in Construction Sites

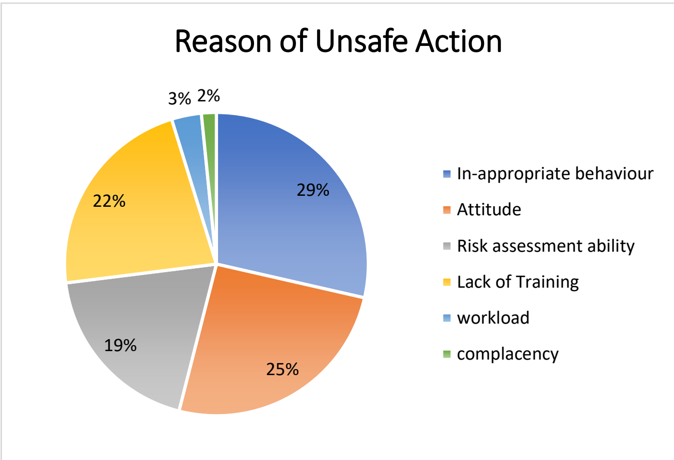

Figure 5.8: Causes of Unsafe Actions

As directed by the literature review unsafe actions by humans are the ultimate cause of accidents on construction sites (Bird, 1974; Heinrich *et al.*, 1980; Reason, 1990b). The involvement of the human factor in carrying out unsafe actions directed the research to explore the attributes of human factors affecting human actions towards the work. Therefore, human factor attributes had been explored through the literature review and found a list to be validated by the construction professionals. Khalid *et al*., (2021) through an extensive literature review classified personnel attitude, safety perception, commitment to work, training and experience as attributes of the human factor that need to be managed for appropriate safety management. The human factor attributes are also called 'performance shaping factors (PSF)' in human reliability analysis terminology. The distributed survey validated these attributes as well as human attitude and behaviour found to be the biggest hurdle in carrying out the construction activities safely. Furthermore, the Likert scale has also been used to rate the importance of these attributes on a scale of 0 to 5 i.e. "not important at all" to "extremely important". The Likert scale was used to rank the human factor safety attributes based on the understanding of the participants. It has been found that human behaviour and attitude share a significant count in the human factor. This also helped the research to consider human behaviour in the framework which has been achieved by proposing an immersive framework to assess the worker's behaviour in an immersive environment. Figure 5.9 illustrates the impact of each of the human factor attributes on accident causation whereas, Figure 5.10 presents the rank of each of the human Factor attributes rated by the respondents.

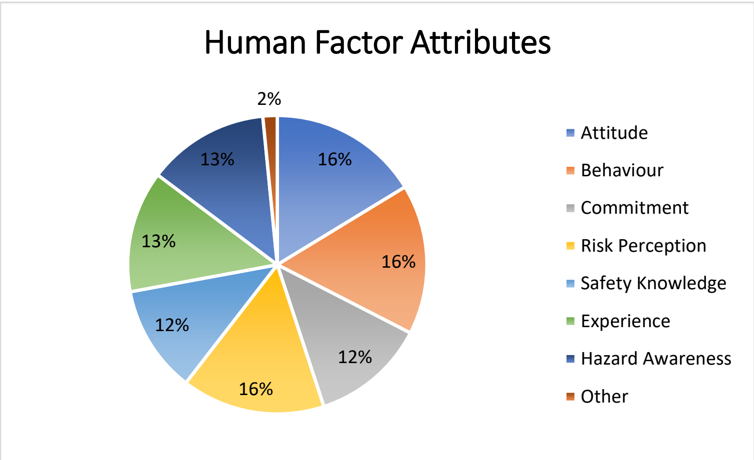

Figure 5.9: Human Error Attributes Involvement in Accidents

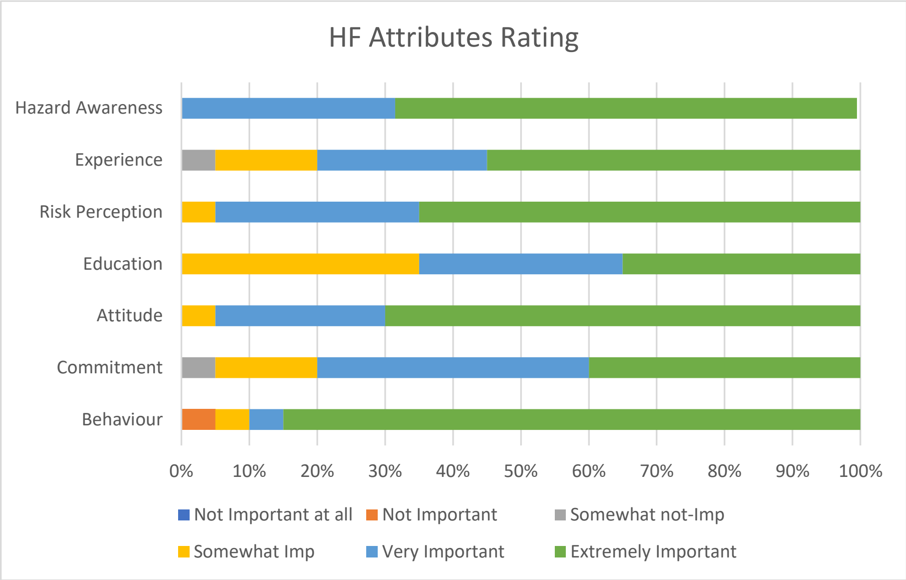

Figure 5.10: Human Factors Attributes Scaling

The study explored in-depth insight into the root causes of human error to develop a framework to manage human error in pursuit to reduce accidents in the construction industry. The participants revealed that most of the incidents are the result of human actions which are usually triggered by human personality traits, background and experience. Based on these findings the human error causation model according to the H&S professional in the construction industry has been developed shown in Figure 5.11.

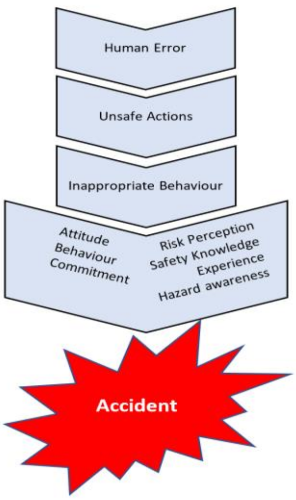

Figure 5.11: Accident Causation Model according to Respondents

5.1.3. Research Findings on Human Reliability Analysis (HRA)

These findings made it inevitable to manage HF for robust safety management in the construction industry. The literature review has rigorously examined the human factor management techniques being used in the complex socio-technical and safety-critical industries. Human Reliability Analysis (HRA) has a long history of managing the human factor in many industries, however, it could hardly make a limited usage in the construction industry. As mentioned in the literature, HRA is a systematic method to identify, quantify as well as mitigate human error from the complicated organisational process. As the literature revealed limited usage of HRA in the construction industry, therefore, it was worthwhile to seek the participant's views on the use of HRA. Surprisingly many participants were unfamiliar with human reliability analysis used in other industries for human error assessment. About 52% of the participants involved in the research didn't know any method for human reliability analysis, the rest of them knew about human reliability assessment, however, no evidence has been found on the usage of HRA throughout their experience as H&S professionals. Moreover, the majority of the respondents didn't know any popular HRA method as illustrated in Figure 5.12. According to these findings, it can be anticipated that the construction industry doesn't use any human factor management technique and rather rely on traditional risk assessment methods.

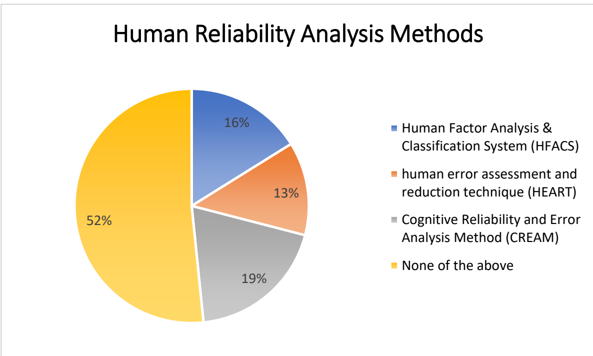

Figure 5.12: Familiarity with Human Reliability Analysis Methods

The accident investigation studies in chapter 3 as well as in the previous section (section 5.3.2) of this interview study highlighted the human factor as one of the prominent causes of accidents in the construction industry causing most accidents, however, no professional practice to manage human factors has been identified by the H&S professionals in the construction industry. Moreover, most of the respondents were not familiar with the human reliability analysis methods substantially used in other industries for human factor management. This validated the research standing to develop the framework to analyse and manage human factors of the safety performance of the construction industry.

Therefore participants have then inquired about human error assessment for this research to develop a novel HRA method for the construction industry. Therefore, regarding the question on HF management, 73% of the participants stated that the human factor should be assessed for the critical tasks presented in Figure 5.13. Following the above question, they have also been asked about the HF assessment method, majority of them (around 32%) agreed that 'measuring HF attributes' could help to assess human factors however, others mentioned 'risk assessment', 'specialist judgement', 'method statement' as illustrated in Figure 5.14. Hence, the development of HRA for the construction industry sought to explore the methods 'human error attributes' could be measured. Another opinion found in this question was 'risk assessment', which is also the most famous method in the construction industry, however, in the literature, the risk assessment has not been found enough for human error assessment and elimination.

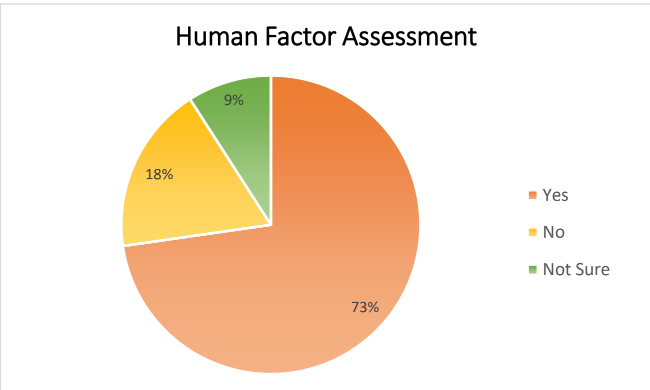

Figure 5.13: Human Factor Assessment

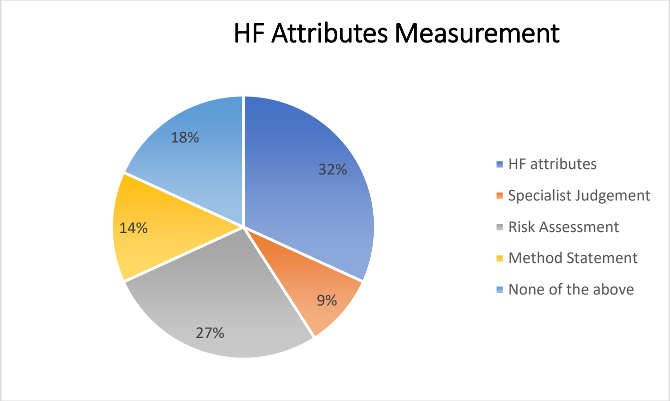

Figure 5.14: Human Factor Measurement

Afterwards, a series of questions have been asked to the respondents to identify the measures/determinants of human factors attributes/performance shaping factors (PSFs). Each question had been designed to inquire about the measures of each attribute/PSF in an immersive environment. For instance, the measure of 'behaviour' in the immersive environment has been explored as 'actions', and 'time'. Similarly, other measures have been explored to develop a framework for the measurement of PSFs in immersive environments. This has been achieved by asking the safety professional number of questions with a diverse range of options to select from. After the detailed analysis, the determinants of human factors according to respondents are; 'human actions', 'risk perception', 'hazard identification', 'attention to detail', 'time', 'safety knowledge', 'communication', and 'persistence' shown in the Figure 5.15.

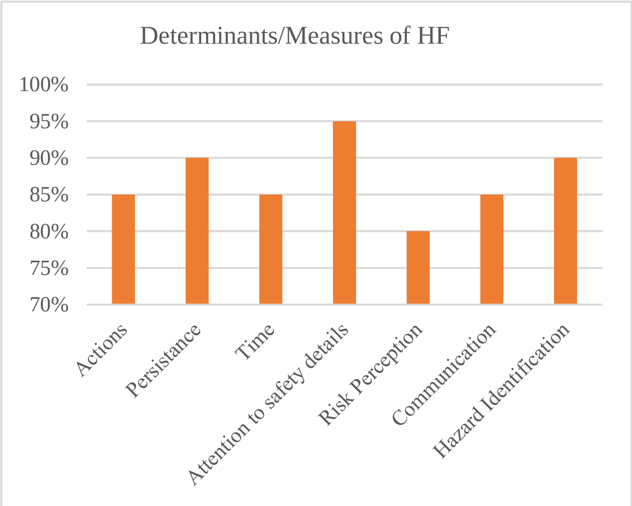

Figure 5.15: Determinants/Measures of Human Factor Attributes/PSFs

Lastly, unlike the typical HRA method which usually utilized either specific calculation or expert judgement to quantify the human error assessment. This study intended to use immersive technology for H&S performance improvement, which has also been examined rigorously in the literature review. The literature also revealed the application of immersive technology in the construction industry as well as its effectiveness in visualising safety details. Based on this, the study aimed to inquire about the respondent's understanding of immersive technologies and how this advanced technology can help improve or resolve safety issues in the construction industry. This led to asking a series of questions on the possible use of immersive technology in human factor assessment.

Hence, the respondents were asked their preferred method to assess human error and most of them did agree that immersive technology could be helpful in the assessment of human error as illustrated in Figure 5.16. The respondents have also mentioned other ways of assessing human error for instance verbal communication, however, immersive technology has been provided better for safety assessment and risk analysis (Sacks, Perlman and Barak, 2013b; Zhao and Lucas, 2015b). Moreover, based on the immersive human error assessment the respondents accepted the fact that the human factor can be managed through immersive technology. Similarly, safety training has a significant role in carrying out the construction process safely. Immersive safety training has already been recommended by the researchers and has also been practised as mentioned in the literature (Horne and Thompson, 2008; Guo, Li and Li, 2013b; Park and Kim, 2013b). The questionnaire asked the respondents about their opinion on immersive technology and whether this can help to manage the human factor shown in Figure 5.17. Most of the respondents agreed with the idea of using immersive training to eliminate human error as shown in Figure 5.18.

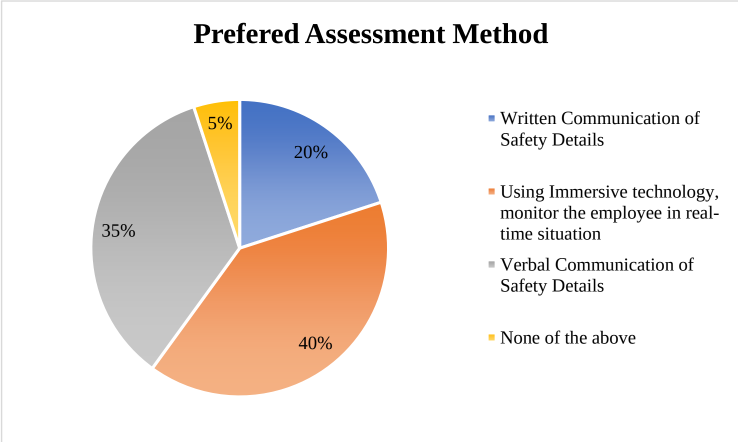

Figure 5.16: Preferred Human Error Assessment Method

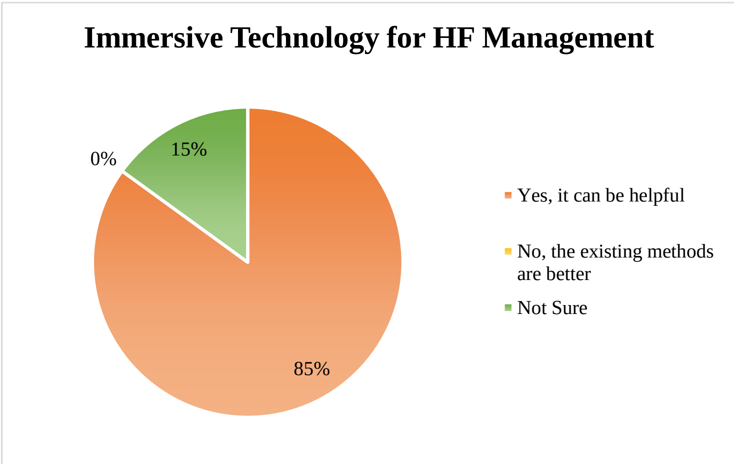

Figure 5.17: HF Management Using Immersive Technology

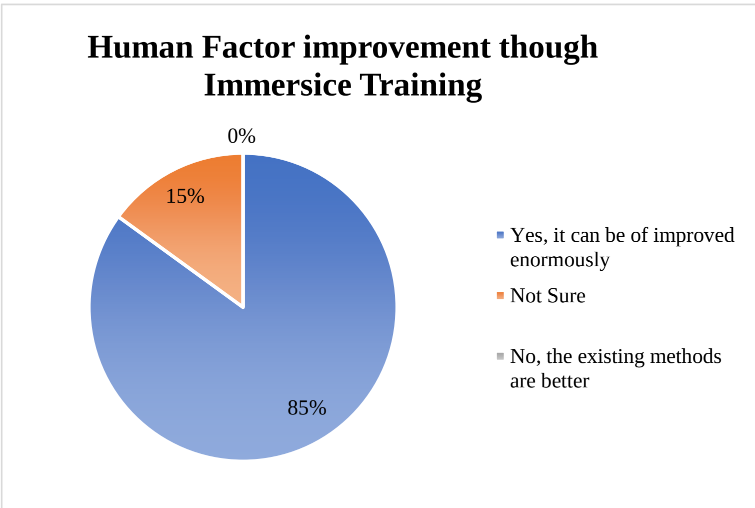

Figure 5.18: Immersive Training for HF Management

Although the research found intriguing and insightful findings on accident causation and human factor involvement in the incidents it has validated the interview findings as the most prominent and substantial factor causing most of the accidents. However, the literature review also highlighted the concept of systematic H&S management in complex socio-technical systems. With the technological interventions and the construction of complex projects, several researchers related to H&S have strongly recommended systematic safety management rather than blaming the site workers for the accident.

5.2. Framework Development

5.2.1. Framework Development Stages

The development of the novel framework for robust health and safety management has been carried out by rigorously following these steps;

1. Identify the causal factors of accidents through critical analysis of the literature and systematic study (Chapter 2).
2. Explore the contemporary safety methods to analyse and evaluate the causal factors through literature and systematic study. (Chapter 3).
3. Based on the above findings develop a research instrument to embed construction professionals' input on identified causes and to propose a potential framework for safety management. (Chapter 5).
4. Develop an immersive human reliability analysis (IHRA) Framework to evaluate human error during construction activity (Chapter 5).

Each of these stages has been discussed rigorously in the next sections.

5.2.1.1. Accident Causation Factors Identification

A critical analysis of accident causation factors has been carried out in Chapter 2. More than 100 articles have been examined using a tailored designed methodology and around 60 causal factors have been identified (Khalid, Sagoo and Benachir, 2021). The leading factors affecting safety management found were; organisational, managerial, regulatory, social, environmental, and personnel/human factors (Aksorn and Hadikusumo, 2008; Ismail *et al.*, 2012; Wang, Zou and Li, 2016; Gunduz and Ahsan, 2018; Othman *et al.*, 2020; Khalid *et al.*, 2021). Further investigation into the causing factors revealed human factors as the most prominent factors contributing to about 80% of accidents in construction sites (Baysari *et al.*, 2009; Guo, Yiu and González, 2016; Fan *et al.*, 2020; Khalid, Sagoo and Medjdoub, 2022). Reason (1990b) associated human error as a major cause of accidents that occur when not taken into account in safety management. Similarly, many accident cause studies cited human error as the main cause of accidents (Haslam *et al.*, 2005; Kariuki and Löwe, 2007; Edmonds, 2016a). The in-depth studies on the human factor, its mechanism, and its effects have been carried out in Chapter 3.

After identifying the potential factors of accidents, the research aimed to further investigate the factors and find out the root causes of accidents. Based on its damaging effects on the construction industry as well as increased fatalities, many scholars have critically examined the human factor to reduce associated risks in the safety-critical industries (Suraji and Duff, 2000; Habibi and Pouya, 2015; Jin *et al.*, 2019; Winge, Albrechtsen and Mostue, 2019; Ünal *et al.*, 2021). For instance, H.W. Heinrich was the pioneer researcher to work on the human factor and analysed the mechanism and associated causes. He presented a theory called 'the domino theory which cited unsafe actions and unsafe conditions as the triggering causes of accidents (Heinrich *et al.*, 1980). Afterwards, several scholars studied the causes and effects of human factors and presented numerous theories. A detailed examination of accident causation theories has been presented in Chapter 3. The in-depth insight into the accident causation models portrays human actions, behaviour, attitude, commitment, risk perception, hazard awareness and safety knowledge as influential factors of human error.

To further validate the research findings from the literature and further investigate the problem identified, quantitative research utilizing the questionnaire has been carried out focused on H&S professionals in the construction industry. The quantitative study not only validated the literature review findings on the human factor as the root cause of the accident but also identified intriguing facts on human factor management and practices according to the professional's knowledge and experience (discussed in section 5.3). Along with validating the root causes of accidents, health and safety experts have also highlighted the significance of top management involvement in regulating safety as well as managing human factors. Moreover, human factor attributes acknowledged by H&S experts were; behaviour, attitude, risk perception, knowledge, commitment, and hazard awareness (discussed in section 5.3). Hence, after the identification of the potential issues associated with H&S in the construction industry, the research intended to examine the methods or practices used in the industry for human factor management to further identify the shortcomings or areas of improvement.

5.2.1.2. Contemporary Human Factor Management Techniques

On successful identification of the research problem, this research routed towards the second research question (Q2) exploring the contemporary methods used in the construction industry to manage the identified cause of the accident. With immense surprise and misfortune, only a little evidence of human factor management has been found in the construction industry which had also been validated through the questionnaire survey. The traditional safety management system used in the construction industry has been discussed in Chapter 2, moreover, this research took the privilege to propose and also publish a robust safety management system considering potential factors causing accidents on construction sites (Khalid, Sagoo and Benachir, 2021). The research found that the traditional health and safety practices in the construction industry are not aligned with the root causes of accidents, hence, do not consider human factors in a complex dynamic socio-technical system while planning as well as execution stages of construction projects (HSE, 2009; Moaveni, Banihashemi and Mojtahedi, 2019; Priska Sinabariba *et al.*, 2020; Hou *et al.*, 2021).

According to the research findings, the current health and safety systems used in the construction sector should be more resilient to human errors. Construction health and safety professionals are well aware of the causes of accidents, but quantitative studies have shown that no HF control methods or techniques are used in the construction industry. Human reliability analysis (HRA) is a commonly used method to identify, evaluate and mitigate human error in many safety-critical industries from human factor management (Hou *et al.*, 2021). As aforementioned, HRA is a qualitative or quantitative technique to analyse the contribution of humans to potential error (HSE, 2009). Chapter 3 has critically and thoroughly discussed the development and working of several HRA methods to manage personal characteristics and behavioural aspects of the workers in a complex human-machine system (Ung, 2015). For instance, an innovative method presented at the expert meeting was the "Human Reliability Error Rate Prediction (THERP) Technique" for modelling human reliability in the nuclear industry in response to the tragic nuclear accident on Three Mile Island. Afterwards, several HRA methods have been developed and successfully used in different industries to quantify human reliability under complex situations (Boring, 2012).

5.2.1.3. Relationship between Causal Factor & HRA

As mentioned earlier, the rigorous investigation of H&S factors unveiled human factors as a great cause of concern for the construction sector (Baysari *et al.*, 2009; Hongling *et al.*, 2016; Fan *et al.*, 2020). Accident causation models (ACM) are critically examined in Chapter 3, explaining the process involved in the execution of accidents as well as explaining the relationship between causal factors and accidents. ACM are the retrospective way of accident prevention by analysing the accidents and exploring the factor (Mitropoulos, Abdelhamid and Howell, 2005b). H.W. Heinrich’s ‘Domino Theory, Peterson’s ‘Multiple Causation Theory’, Bird’s Theory, and Reason’s ‘Swiss-Cheese Model’ have rigorously explained the accident causation process and highlighted the significance of human factors as well as explained how human error propagates the accidents. For instance, the Swiss-Cheese Model disseminates the accident into organisational influence, managerial influence, unsafe act, and human error shown in Figure 5.19.

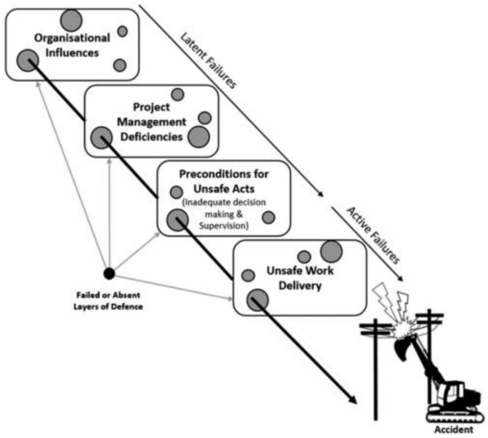

Figure 5.19: Relationship between Human error and Accident (Heinrich et al.*, 1980)*

Empirical research conducted has also validated human error as the main reason behind accidents on construction sites. Evidently, ACMs are the retrospective way to study accidents and identify the causes that could initiate active or latent failures. However, for the dynamic socio-technical complex industry and distinctiveness in the construction project features, ACMs do not help to manage human factors for accident prevention (Jenkins *et al.*, 2010; Apostol-mates and Barbu, 2016). On the other side, HRA is a well-known method to analyse the human behavioural aspects of human error prevention. Subsequently, the construction industry has not yet developed the culture to utilise the HRA to manage human factors. The conventional method of dealing with any form of risk linked with the building process is known as "risk assessment" in the construction industry (Pinto, Nunes and Ribeiro, 2011). However, Aven (2003) argued that ‘reliability analysis’ and ‘risk assessment’ are two separate subjects with a great deal of overlap. Hence, the probabilistic human error evaluation is inevitable to be carried out to manage human factors using the HRA technique.

5.2.1.4. Immersive HRA Framework Development for Construction Industry

The role of HRA in human error management has a significant history that has been rigorously discussed in Chapter 3. However, the construction industry has not yet benefited from the HRA, and hence human error has an enormous role in accident causation in the construction industry responsible for 80% of the accidents (Guo, Yiu and González, 2016). Although technology developments in the construction business have aided in risk assessment and safety management, human error is still known to have disastrous consequences in the construction sector. Scholars have argued that risk assessment covers the big spectrum of safety management, however, the reliability analysis technique has specifically developed to study the human behavioural aspects of a system. According to the literature and the empirical research, little emphasis has been paid to reducing human error in the construction process; nonetheless, academics have offered recommendations to employ HRA.

Limited evidence of HRA use in the construction industry has been found in the literature as well as through quantitative research. Researchers, however, suggested the potential use of HRA in the construction industry for human error management. For instance, Moaveni, Banihashemi and Mojtahedi (2019) assessed the HRA models and stated that HRA might aid in reducing the likelihood of human errors in the construction sector. Similarly, Priska Sinabariba et al. (2020) implemented the HRA method to analyze the behaviour and associated risks in the construction sector in Indonesia. Similarly, several H&S researchers have recommended the use of the HRA technique to reduce human error risk (HSE, 2009; Hou *et al.*, 2021). However, this technique has not been introduced in the construction industry as a safety management practice. A similar trend has been found in the quantitative research on HRA methods, 73% of the respondents found familiar with HRA, however, no evidence has been found of using HRA for human error assessment.

Henceforth, to successfully introduce the HRA technique in the construction sector, the investigation of limitations was inevitable. The intricacy of HRA procedures is one of the key limits found in the literature validated by the survey respondents. Other limitations found were; the sophisticated nature, specialist knowledge of the HRA technique used, nature of the construction industry, and unreliability of HRA methods (discussed in Chapter 3). Based on established arguments, the construction industry undoubtedly needs the HRA method specifically designed for the industry. Therefore, two requirements have been recognised for the development of the HRA method for the construction industry;

i. Compatible with contemporary safety management systems,
ii. Convenient for safety experts.

These requirements have been achieved by introducing the concept of 'Immersive' in HRA development. The literature review has revealed that contemporary methods couldn't make their way to the construction industry because of the complexity of their usage. Current methods are usually based on either expert's judgement or complex calculation. Therefore, based on the literature review, quantitative research findings and effectiveness as well as the successful application of immersive technologies in many fields, this research found immersive technologies a pertinent choice for the development of the HRA. The application of immersive technology for development will have the following benefits.

i. User-friendly: The literature has revealed that appropriately developed immersive applications will not only have improved outcomes but will also be easy to adopt by the users.
ii. Reduced Risk: One of the key benefits of this technology is being risk-free and has been successfully used with exceptional results for training purposes in many industries (Loosemore and Malouf, 2019).

iii. Conceptual Blending: Immersive technology helps the user to blend between real and virtual work that enhances their learning performance (Enyedy, Danish and DeLiema, 2015).

iv. Cognitive Experience: The research has revealed that immersive technologies have helped users to process a large amount of information embedded through their learning context which eventually enhanced their cognitive ability (Hsu, 2017).

v. Constructive Learning: Another useful aspect of immersive technology found was a constructive learning experience that allows the learner to actively engage with the learning material as well as recall the previous knowledge to develop new knowledge (Huang, Rauch and Liaw, 2010).

5.2.1.4.1. IHRA Framework

The above analysis of the limitations of traditional HRA methods and the appropriateness of immersive technology lead to the development of immersive human reliability analysis (IHRA). The traditional HRA are typically based on PSFs to identify the HEPs, therefore, the proposed immersive HRA has been developed on the same method shown in Figure 5.20. However, for the immersive HRA development, the assessment measures/enablers identified through the quantitative study for immersive reliability assessment are; human actions, time, risk perception, safety knowledge, hazard awareness and communication shown in Figure 5.21 below. Moreover, 'immersive activity designed', and 'complexity' was found as two variables for the design of IHRA. The schematic diagram of the proposed IHRA is shown in Figure 5.22 below.

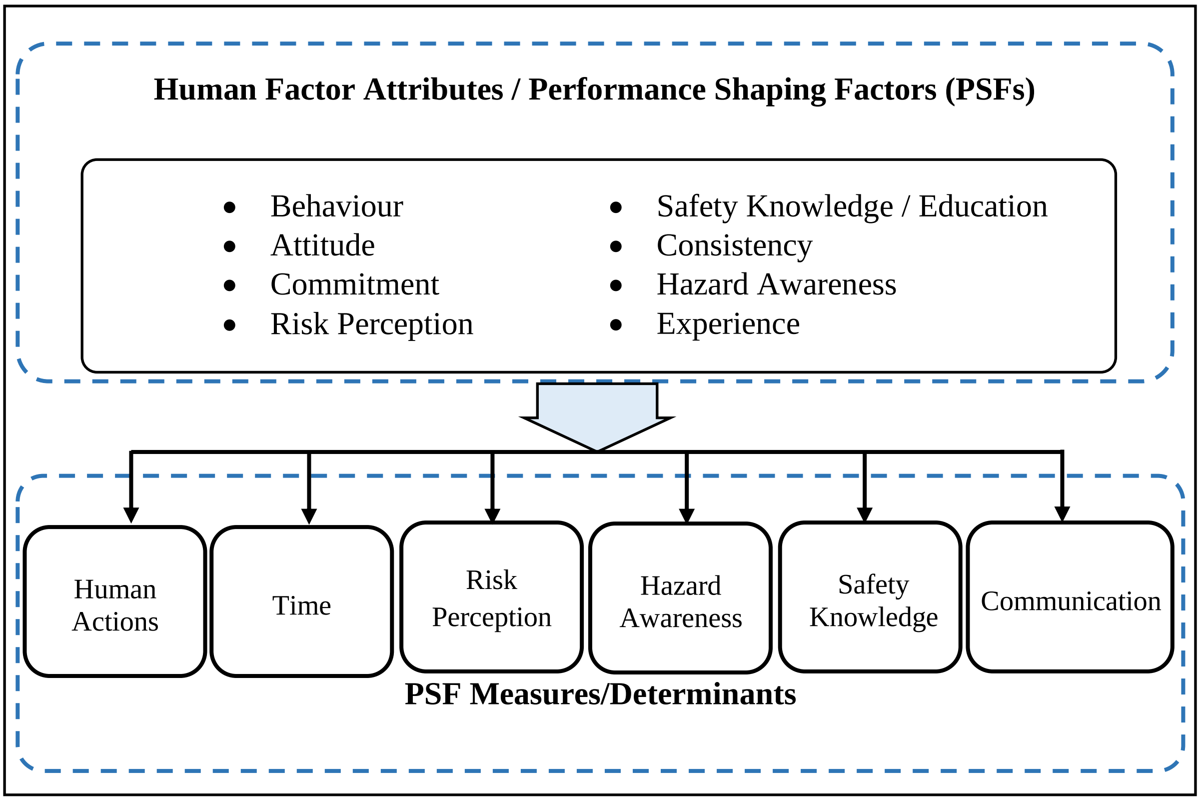

Figure 5.20: Performance Shaping Factors (PSFs) Measures

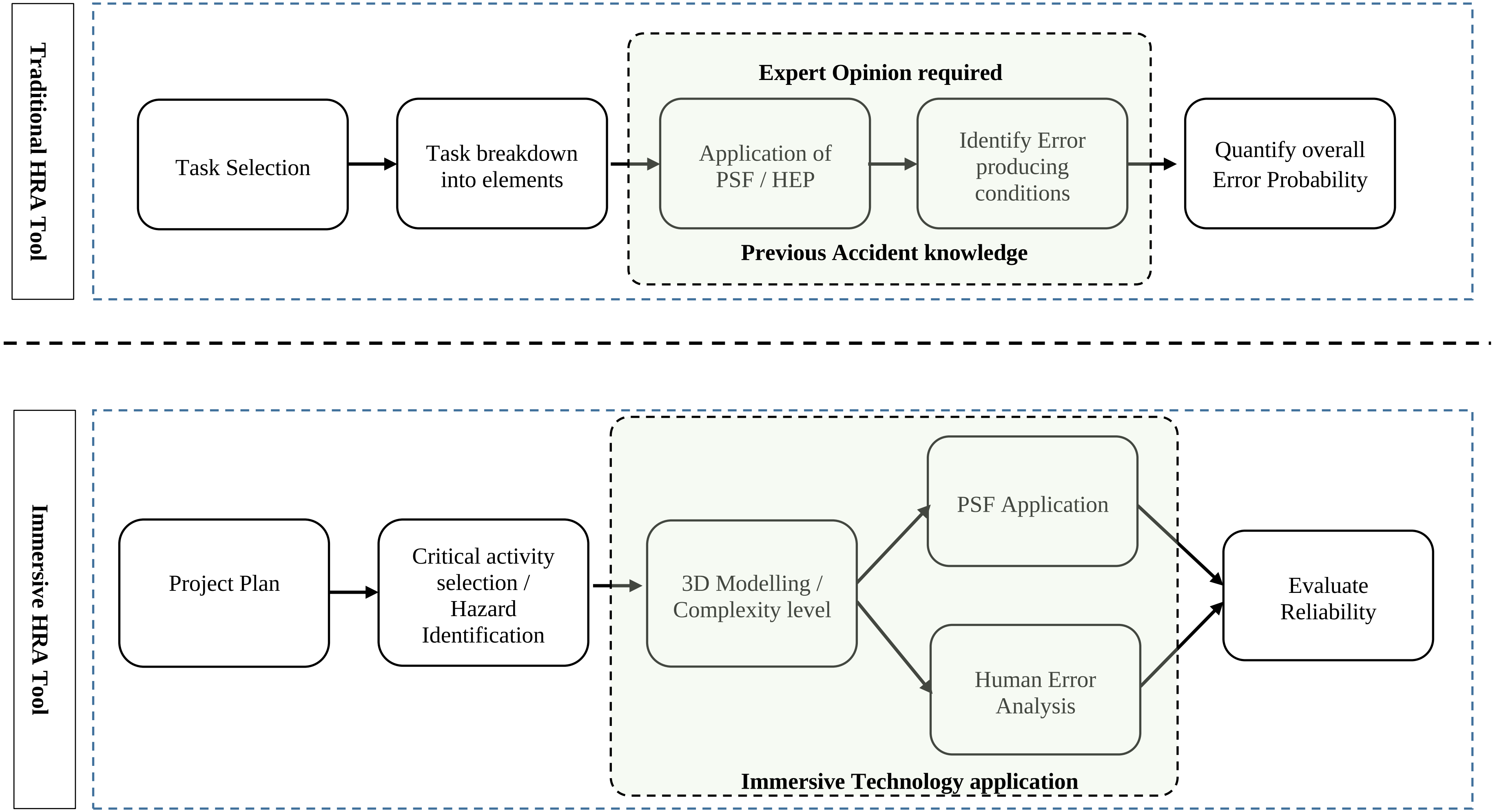

Figure 5.21: Comparison between Tradition and Proposed Immersive HRA

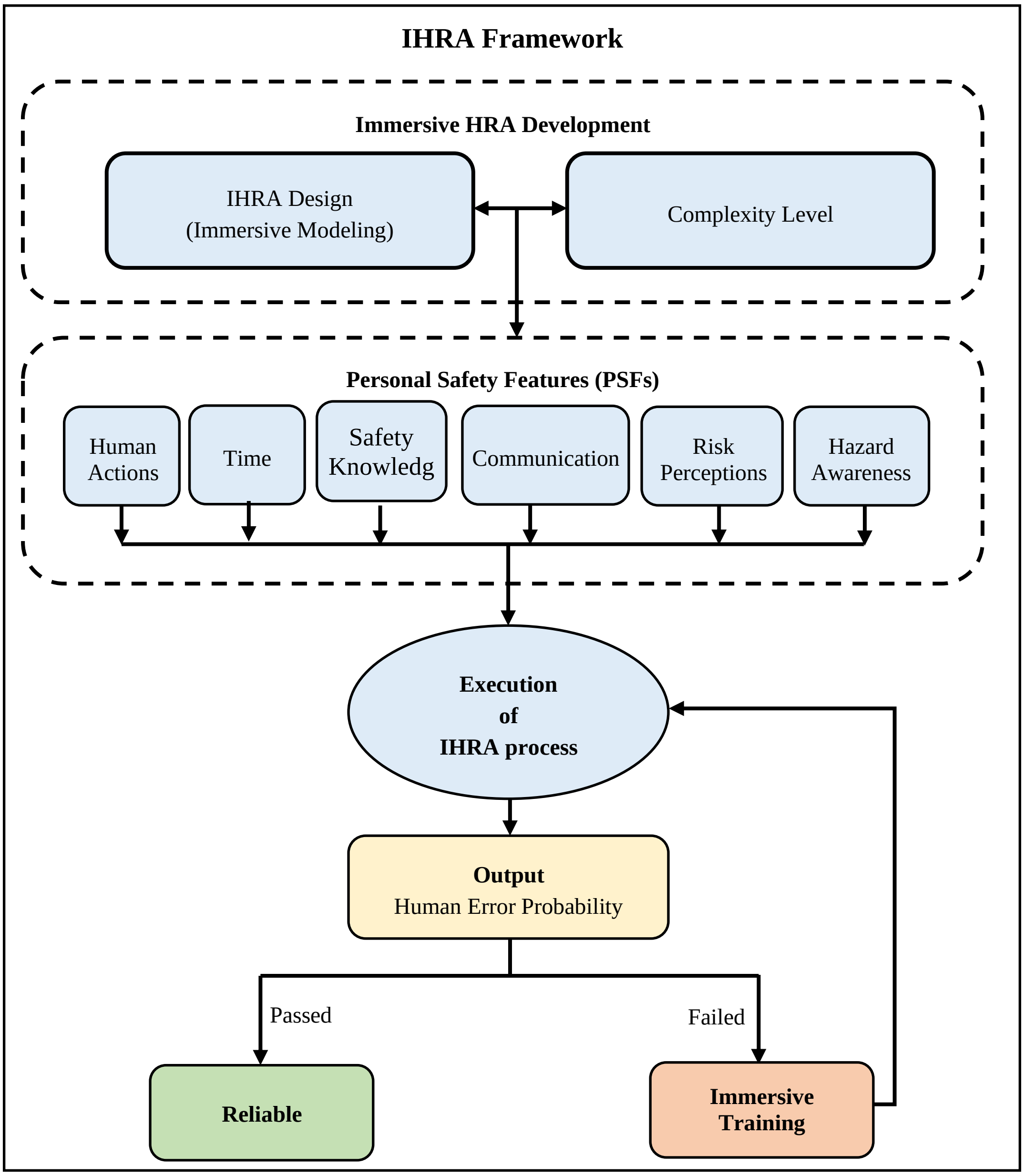

Figure 5.22: Immersive Human Reliability Analysis Model (IHRA)

5.2.1.5. Immersive Safety Management Framework

Based on the research finding and employing the IHRA model, the research proposes a Framework for human error mitigation below in Figure 5.23. Chapter 3 has explicitly reviewed accident causation models which demonstrated the error mechanism. The accident causation models have accused unsafe conditions and unsafe actions as the ultimate causes of accidents. This framework has been developed based on two underpinned parameters; (i) environmental risk mitigation, and (ii) human error mitigation; employing immersive technology. Both underlying parameters run simultaneously in the proposed framework that carries out safety in three stages. (i) Modelling, (ii) Analysis / Assessment, and lastly (iii) Error Management.

As illustrated in the proposed framework, the identification and elimination of human errors from the construction process will be achieved in different phases i.e. 'modelling and simulation', 'human reliability analysis', and 'human error management'. Stage 1 of the proposed framework associates the project information to develop the project models which can be carried out at the initial stages of the construction project. This allows the safety professionals to develop a 3D model of the construction project for the H&S risk assessment and develop the simulation model of the critical project activities. This can be achieved by embedding the developed 3D model within the immersive tools and creating the essential functions to carry out the planned construction activity in the immersive environment.

Subsequently, stage 2 is the key stage in this framework that illustrates the carrying out of the risk assessment as well as the human reliability analysis based on the model and simulation developed in the previous stage. As this research figured that through accident causation studies that unsafety conditions lead to human error along with other performance shaping factors (PSFs). Therefore, the proposed framework allows the safety managers to carry out the risk assessment of the construction project and identify the risks as well as the activities which require human reliability analysis. Once the unsafe conditions are identified then the next phase is to run an immersive HRA simulation based on PSFs shown in Figure 5.22. The complexity level of the developed simulation will define the accuracy and success of the HRA. This phase will allow the safety professionals to carry out human reliability analysis in the immersive environment and identify the possible unsafe actions of the workers. Lastly, stage 3 of the framework enables the elimination of unsafe conditions and actions from the construction process by mitigating the identified risks and through immersive training of workers with a low score of human reliability analysis.

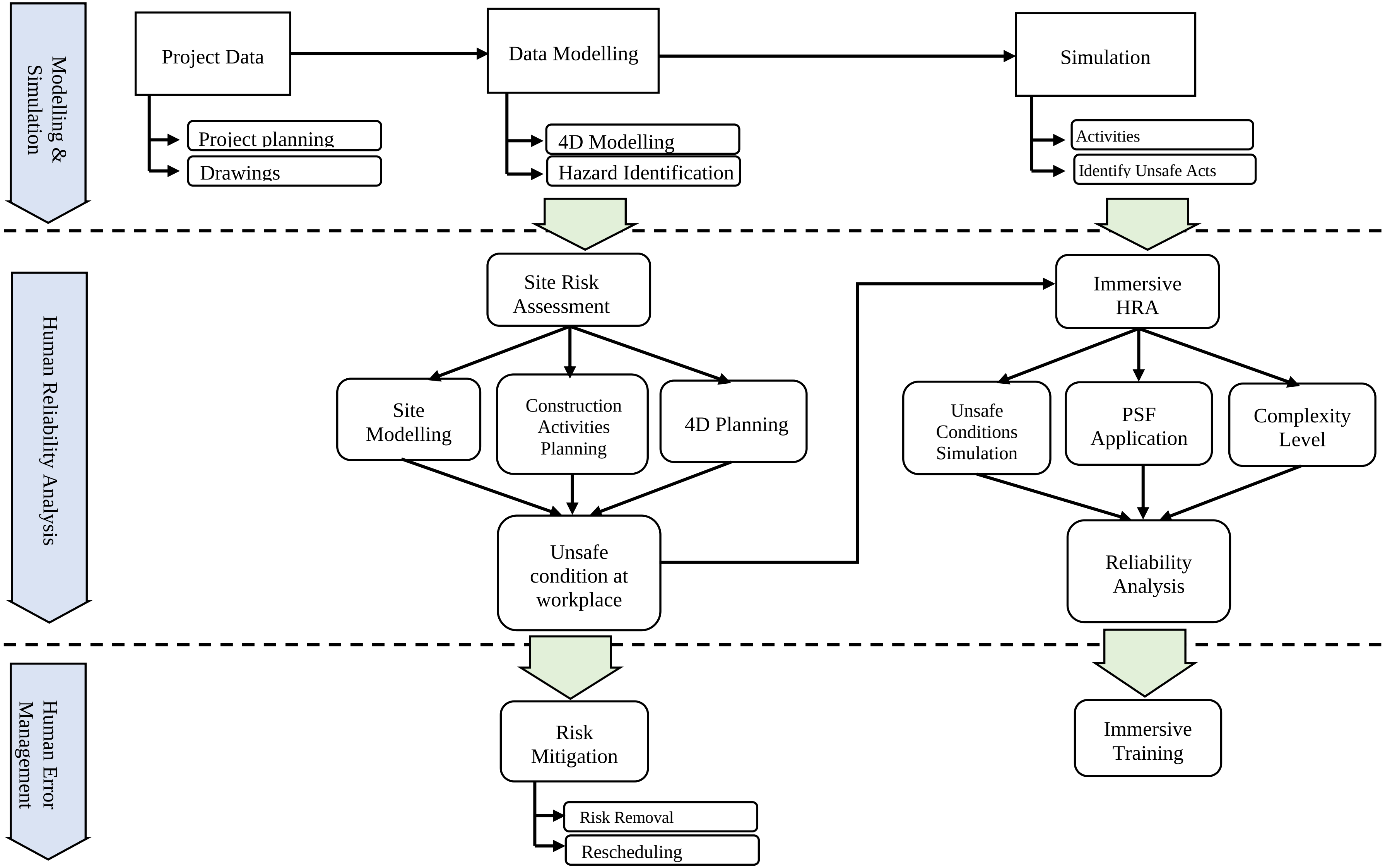

Figure 5.23: Safety Management Framework

5.3. Chapter Summary

This chapter examined the research questions on accident causation and the factors involved to establish a relationship between them. Human factors have been identified as the main cause of accidents in the construction industry through rigorous literature review research. Hence, to eliminate the accident causation factors, several methods have been examined to manage human error through a literature review which has been validated by quantitative research findings. Afterwards, based on the research findings a novel Framework to manage human factors has been developed in section 5.2.1.4 of this chapter.

Chapter 6: Research Validation & Findings

6. Introduction

The previous chapter discussed the research findings as well as presented a robust framework for improved H&S management. This chapter validates the research findings from the previous chapter through in-depth interviews of H&S professionals in the construction industry. A detailed discussion on the participants, interview strategy and the finding has been carried out to further investigate the research questions as well as validate the research findings to improve the H&S performance of the UK construction industry.

6.1. Research Validation

The validation of research findings is the fundamental component of any scholarly research endeavour. Validation describes how well the acquired knowledge covers the real field of research (Ghauri and Gronhaug, 2005). Similarly, Taherdoost (2018) defined research validity as a concept used to judge how excellent a research response is for any particular topic. Moreover, research validation often stands opposite to verification. Validity is defined as "measuring what is meant to be measured" (Andy Field, 2005). Contrarily, verification guarantees the technical accuracy of research products, such as simulation models (Lucko and Rojas, 2010). As both terms are common in the technical and management literature, they are often used ambiguously or interchangeably. Generally, verification is often concerned with "doing things correctly", whereas validation is concerned with "doing the right things". Therefore, this research aims to validate the research findings as well as the framework developed through rigorously conducted research. The purpose of the validation has been to make the proposed framework more effective and thus further align the research findings with the industrial needs.

The literature revealed two kinds of research validation; (i) internal validation, and (ii) external validation (Robert K. Yin, 2014). Internal validity is closely tied to the idea of the cause-and-effect phenomenon and is concerned with the derivability of relationships inside data. Internal validity can be jeopardised by a variety of issues, including ill-defined theoretical models with misleading correlations or connected explanatory factors, biases in data collecting that make comparisons inefficient, and the inability to consider alternate hypotheses during data analysis (Leedy and Ormrod, 2001). However, external validity refers to the degree to which a study result can be generalized outside the immediate study sample. External validity can be jeopardised by several factors, including a lack of statistical integrity in sample size selection and data collection, the existence of any exceptional conditions during the research efforts, and the simplicity of the phenomenon under investigation (Leedy and Ormrod, 2001).

Other types of validity mentioned in the literature include face validity, criterion validity, content validity, and construct validity (Taherdoost, 2018). Face validity is a non-statistical subjective evaluation that seeks the opinion of non-researchers on the validity of a certain study. Another non-statistical technique is content validity, which focuses on establishing whether the substance of a study accurately reflects reality. The definition of criterion validity found in the literature is “the degree to which the outcomes of one assessment instrument coincide with another, seemingly related measure”. Whereas, construct validity relates to the appropriateness of operationalizations of theoretical conceptions. In other words, construct validity is focused on ensuring that a research endeavour is measuring what it is meant to be measured following its stated objectives (Leedy and Ormrod, 2001).

Construction engineering and management research investigate real-world tools and procedures to increase the construction industry's efficacy and efficiency. Experiments, observational studies, surveys, modelling and simulation, case studies, theory development, case studies, and interviews have all been employed in construction engineering and management research for validation (Lucko and Rojas, 2010). The construct validity approach to validate the research findings has been utilized which is a common validation approach used in the social sciences and behavioural research. The construct of the research design is frequently defined as "the extent to which the evidence being accumulated is an accurate depiction of latent constructs that may draw on a variety of sources and types of data, as well as being pertinent to the theory that the scientist is seeking to build" (Straub and Gefen, 2004). The construct itself may be understood as a social construction, characterized by a collection of intellectually produced measures that are neither self-evident nor inherently "true". In this research, a literature review, safety regulations, government reports and a questionnaire survey with safety experts in the UK construction industry have been used in providing multiple data sources for formulating the proposed framework for improved safety management. All these data sources were valid and acceptable therefore the internal validation of the research findings, however, for the external validation of the proposed framework, interviews have been conducted.

6.2. Validation Technique

As aforementioned, in the construction management industry experiments, observational studies, surveys, case studies, theory development, case studies, and interviews are the most frequently used techniques for research validation. For this research, interviews with safety and behaviour experts have been conducted to validate the proposed framework built on research findings.

6.2.1. Sampling & Interview Arrangements

Semi-structured (qualitative interviews) were considered appropriate for this study to investigate the health and safety procedures and mitigation measures utilised by construction experts. As this study was based on a real-world situation, especially in the construction sector, therefore, the researcher was well familiar with the sample participants to acquire data for research validation. Hence, the non-probability sampling technique has been selected as an appropriate choice. Moreover, the initial research findings highlighted human factors as the main causes of accidents that involve personnel traits, for instance, behaviour towards safety. Therefore the sample audience identified for this study has been divided into two groups;

i. Lead safety experts in the UK construction industry to validate the proposed framework.
ii. Behavioural experts in the UK construction industry critically and rigorously analyse the framework in relation to managing behavioural aspects towards safety.

Based on the defined sampling criterion, the interviews with the safety and behaviour experts have been carried out with twenty (20) experts. Fifteen (15) out of twenty were lead safety experts whereas, the remaining five (5) were behavioural experts in the UK construction industry. This interview strategy has been adopted to validate the research as well as the framework. As semi-structured interviews have been selected for this research, therefore a set of questions have been developed to cover every aspect of the research. However, open-ended queries have been included in the interview so that follow-up questions could be asked based on the participant's responses.

6.2.2. Data Analysis

As aforementioned, data Analysis begins with the breakdown, separation, or disassembly of research materials into parts, pieces, elements, or units. A qualitative data analysis approach has been selected for the analysis of interview data.

6.2.3. Qualitative Data Analysis

A crucial element of qualitative analysis is the emphasis on text rather than numbers. The 'text' that scholars analyse is typically an interview transcription or records from participant observations; however, the text could be referred to as imagery or any other pictorial evidence that the researcher studies (Lacey and Luff, 2001). Different data analysis stages mentioned by Lacey and Luff (2001) are;

i. Documentation: It begins with the data collection and writing of the transcript.
ii. Organisation: Data organization and classification into concepts.

iii. Connection: Identify the relationship between the data and explore how different concepts may influence each other.

iv. Corroboration: Corroboration/legitimization is accomplished by the evaluation of alternative hypotheses, disconfirming evidence, and the search for negative cases.

v. Representation: presenting the research finding.

For this research, online interviews have been carried out, and in the first stage, the online interviews have been converted to written documentation to undergo the analysis. Afterwards, the interpretative phenomenological analysis (IPA) technique has been used for qualitative analysis.

6.3. Framework Validation

This study implemented semi-structured interviews for the research validation where data is analysed using the Interpretative Phenomenological Analysis (IPA) method which has been selected as the most appropriate method for the analysis of qualitative research. Each of the interviews has been analysed using the IPA method for rigorous analysis to get the best outcomes. As the interview used a semi-structured approach therefore a questionnaire with open-ended questions has been formulated. Moreover, the interview has been divided into three parts to align it with the research objectives. The first section sought information on the current H&S practices that have been practised in the UK construction industry to evaluate the current safety management system against the safety issues highlighted in this study. The essence of this part is to determine how effectively the construction industry is handling those factors affecting H&S in the construction industry. Furthermore, this part will validate the research findings (objective 1) based on which the framework has been proposed.

Additionally, section 2 of the semi-structured interview inquired about the participant's opinion on the accident causation factors and determine their understanding of accidents, the causes, and the system they have in place to eliminate those factors to make the construction site more secure for the workers. This section also validates objective 2 of this study which looks into the finding of the causes of the accidents found during the study. A series of questions have been asked to the participants on the accident causation to have an in-depth perception of accidents and determine if it's aligned with the research findings. Similarly, the last section of the interviews comprehensively inquires the participants about the found most presiding and dominant causes of accidents and eventually validates the proposed framework. Following the aforesaid inductive approach for the data analysis, this study seeks to develop knowledge based on the evidence from the H&S intellectuals in the UK construction industry. Therefore, the inductive approach has been practised for this study to analyse the qualitative data.

Nevertheless, each interview has been conducted digitally because of the restrictions imposed by the government due to the COVID-19 pandemic since 2019. Most of the interviews have been conducted on MS Teams through video calls and a few of them were also conducted on the Phone based on the participant's priority and the internet limitations. All of the interviews were recorded and have been transcribed later for data analysis purposes. Furthermore, most of the interviews have been transcribed by the MS Team itself, however, a few of them have been transcribed manually. Special consideration has been practised to transcribe the videos professionally without any bias. On careful completion of the interview transcripts the IPA analysis method has been used as mentioned above and the following process has been practised.

i. Each of the questions has been read comprehensively multiple times to highlight the preliminary themes.
ii. Once the emerging themes have been identified and clustering has been carried out of the emergent theses for each of the respondents.
iii. Research queries have been analysed based on the emergent themes from each of the questions asked and findings have been summarised.

Each section of the semi-structured interviews has been discussed in detail below;

6.3.1. Participants Demographics

A similar sampling technique has been used for the qualitative research which was practised for the questionnaire survey. The non-probability sampling technique was used since this research was conducted on a real-time topic particular to the construction sector. Furthermore, the goal of this research was to look into the causes of accidents and the shortcomings of present H&S practices in the UK construction industry and explore the methods used for human error mitigation. As a result, the sample population for the questionnaire survey was made up of construction H&S specialists with expertise and experience in the field. As a result, H&S managers, directors, and leads have been chosen and contacted for this study to conduct interviews. Moreover, as the previously conducted research highlighted the human factors that include human behaviour, attitude and perception, therefore, specifically for the interview study safety behaviour managers have also been conducted to also validate the behavioural aspect of the research. The list of participants and their professional backgrounds has been presented in Table 6.1 below. The participants were divided into three safety groups (SG) based on their roles in safety management.

Table 6.1: Interview Participant's Background

Group Title	Background	No of Participants	Organization Type	Background	Experience	Qualifications
SG-1	H&S manager (4) Director H&S (3) H&S coordinator (1) H&S lead (2) CDM regulator (1) Associate H&S Directors (1)	12	Contractor	Infrastructure Building Railways	5-15 years	NEBOSH GradOHS CMIOSH IOSH
SG-2	Safety Consultant (2) CDM H&S service (1)	3	Consultant CDM Service	Railways Building	10-15 years	MCIOB NEBOSH
SG-3	Behavioural Manager (5)	5	Contractor	Infrastructure Railways Building	5-10 years	CMIOSH MCIOB

6.3.2. Health & Safety Practices in the UK Construction Industry

As mentioned above, the first part explored the H&S safety practices being used in the construction industry. The literature review has rigorously explored the traditional health and safety practices and also highlighted their shortcoming, however, to further extend the research findings on H&S practices and specifically to explore the in-house safety management systems in the construction companies, a few questions have been asked in the first section of the interview. Almost all of the H&S professionals who were either the safety leads, safety managers or safety consultants validated the literature review and backed the traditional H&S management system. A traditional safety management system in the UK construction industry comprises complying with the safety regulations, carrying out the risk assessment, developing method statements and designing for safety. For instance one of the participants stated:

> "*So the core requirements are fully embedded in the organisational health and safety practices at work and CDM regulations in principle. My current role is working as consulting engineer and what are in terms of the Highways England project, we are working with three companies to work collaboratively and our work is H&S of the project. Making sure compliance with CDM regulation and providing effective instruction in terms of H&S safety. So the other companies are contractors and we are the consultants doing a risk assessment, developing method statements and then going into looking at machines, material and everything else. So currently this is how our and companies in the UK are complying with the safety practices and regulations". [SG-2]*

This statement indicated how basic H&S safety is practised in the construction industry and as a core requirement, this traditional system has been embedded into every organisation's management system. Moreover, this also indicates the consultant's perception of H&S that exclusively revolves around the CDM regulations. However, besides the conventional H&S, a few companies claim that they go a step further and also have in-house safety management systems to establish a safety culture and make sure everyone works safely and has a safety structure at a corporate level. As one of the participants narrated:

> *"The higher level is done corporately. This got about 50,000 people working around globally so the hierarchy structure put some hearings on the safety down to the organisation. So the global leadership and then regionally. Regions across the globe where we work are Europe, the middle east and then Australia where our organisation works specific and then it also works in North America. Within our region which is Europe and the Middle East, we have regional leadership for health and safety and a big focus of that is around the corporate obligations and process in-house which is called 'Beyond Zero' which is done from induction for anybody joining the business so an over arching concept which tried to eliminate the accidents or eliminate the health risks that come across [….]". [SG-1]*

> *"Safety is managed in my organisation by competent safety professionals and we are working on the philosophy that everybody should go home safely and it's done by the safety professionals. We ask the company or the organisation to have a commitment towards safety and that commitment should be from the highest level down to the people on the ground". [SG-1]*

Similarly, another participant mentioned that:

> *"When we talk about looking at the pre-construction phase. Obviously, we have the hazards we look at those we actually and this is important really important part as part of developing the work plan the surface system of work.*

> *We actually involve the technical experts from the supply chain. and that is part of them actually producing the methodology because they are the technical experts where, where maybe we're not in ensuring that we've got a robust, safe system of work. we have many hulled points before people actually start working. It will also review the work package plan is reviewed by the contractors engineering manager or if you to apply that to traditional construction, then obviously that will go through the project manager. And indeed, the health and safety manager. So it's a lot of hull points before we actually start working". [SG-3]*

According to these H&S professionals, the H&S practices in the construction industry are committed to eliminating the potential risks involved in the construction process through the development of the organisational structure and the introduction of technical experts also helps in identifying the potential risks in design and construction stages. Participants have also indicated that the commitment to safety and through rigorous risk assessment and supervision the accidents can be reduced. However, the perspective of behaviour managers in the construction industry has highlighted the significance of human behaviour in managing safety. According to them, human behaviour is the main cause of accidents in the industry which also validates the research findings which explored that the human factor is the cause of 80% of the accidents. They have further indicated that they have systems in the organisation to influence people's behaviour that helps towards reducing accidents. One of the participants said;

> *"Okay, so we have a couple of things that we work with. First, we have a traditional safety management system from the top-down that involves complying with the safety regulations and doing a risk assessment and method statements. That's the thing everyone does, on top of then we have an in-house safety management system called ABC Model. That's attendance,*

> *behaviour, and consequence. It's either good or bad. Good attitude leads to good consequences and bad behaviour leads to bad consequences. If the ABC model is bad that means a variety of things. Behaviour > not positive, Ignorance > human error, Influence/ peer pressure and it will come with a financial cost". [SG-3]*

Another participant stated that;

> *"It really deep dives into various areas as I'm certain that you're aware of, but we, as part of the people's attitudes we look at, what kind of headspace they are app before they actually attend work and make them challenge themselves. We have the 6C's and two of the C's are a challenge and also care so you know it's a multi-faceted approach on how we ensure the safety of our people out there in the Prevention of Accidents and incidents, we have close calls, hazard observations, positive interventions and also in interestingly we also have those for design as well". [SG-3]*

Nevertheless, it is evident from the participant's responses that construction professionals have different opinions on safety management. Safety professionals working on the construction project sites specifically the safety managers relate safety management to complying with safety regulations, method statements, risk assessment and supervision. Above them is the safety leadership exclusively the safety directors or the HSC executives who have committed to embedding safety in the organisation's culture by promoting good practices to deal with the current safety issues. However, unlike the safety experts, behaviour managers have a different opinion on safety management that is more aligned with the findings of this research. Behaviour managers believe that human behaviour is the main driver of safety and safety performance can be improved instinctively by promoting good behaviour in the organisation. Thus to further explore the safety issues section 2 of the interview inquired the participants about the factors causing accidents on construction sites and review how current safety management systems are associated with the potential causes of accidents.

6.3.3. Accident Causation in the UK Construction Industry

The safety management systems can not be validated completely unless the factors behind the accidents are known. Chapter 2 and Chapter 3 have critically examined the factors affecting safety performance and rigorously reviewed the causes of accidents. Therefore as mentioned above, this section comprehensively inquired the safety experts about the causes of the accidents to validate the research findings. This section of the questionnaire is comprised of a series of questions to note the participant's understanding of accident causation. The two main themes which have been explored in this section were; (i) the causes of the accident, and (ii) how these causes correspond to the safety management systems practices in their organisation. Each question asked had several follow-up questions to have an in-depth insight into the participant's understating of asked queries.

As revealed in the previous section, two kinds of perspectives have been identified in this section as well. It has been found that the H&S consultant's orientation on safety is management driven and they have indicated that management commitment is the main cause of accidents on sites. Therefore for them, good management practices could help to reduce or mitigate the accident during the construction process. As referred by one of the participants;

> *"In my opinion management commitment, ineffective communication about the risk, and understanding between the management arrangements and site operatives. The other aspects we are finding are the mental stress on the worker". [SG-2]*

Nevertheless, the other perspective found during the interviews is oriented more toward the personal failure of the system failure. The emerging themes of accident causation found in this perspective are; human error, communication, human behaviour, human factor and personnel attitude. Moreover, participants supporting this perception believe that safety flows from top to bottom and accidents usually happen due to the human factor involved at the bottom level. For instance one of the participants said;

> *"I think in construction it is a barrier as in construction there's a large contingency of non-English speakers that pretty much because construction industry requires a large influx of you know non-English speakers to fulfil the gap industry has from last 15 to 20 years and I think language is a massive part of the safety". [SG-1]*

Another one mentioned that;

> *"A lot of accidents do happen I think are construction management related or the individuals not complying with the process/system which is there to protect them but the design clearly has a massive obligation to try the design out the hazards before the thing goes to the contractors". [SG-1]*

Similarly, the other factors identified for the causation of the accident are associated with the human factors that also validated the research findings. One of the participant's responses to human factors is narrated below;

> *"There is a number of things that could initiate any accident, for instance, human factor but that's not the only reason. There are also other reasons that include ignorance, safety program failure, system error or technical error". [SG-3]*

To further investigate the causes of accidents and identify how the above-mentioned causes are associated with the accidents. Participants were also asked about any recent accident they have encountered and what causes were identified and what lessons have been learned. The accident causation studies explored from the participant's understanding and experience again validated the human factors as the pertinent reason for the accidents in this construction industry. Several questions have been asked of each participant to have a detailed examination of the accident they experienced and what kind of factors were identified from the accident investigation. It has been established from the participant's feedback that the construction H&S professionals are not familiar with the terms human factor or the behavioural aspect of accident causation. They look at safety from the management perspective, not from the behavioural or human factor perspective. For instance one of the respondent stated;

> *"Yes, there has been a number of accidents on construction sites I have worked with and generally there are a number of repetitive causes. One of the root causes is that people have done something different than the given job description. He changes the method, you know. They sometimes make their own decision on something, that's the first thing. And other things include taking unnecessary risks, wrong risks perception etc". [SG-1]*

Similarly, another one stated that;

> *"I have seen a number of accidents. The first one I remember was there was a fatality and at that time the issue was the temporary structure was over and the excavation and it brought down the support gauge so it might be very aware of utility diversion and temporary works for utilities. So that was probably the biggest learning that I got on to. when the accident involves a fatality there's usually an investigation and HSE would involve in that yes. I think communication was the main issue behind that accident". [SG-1]*

This clearly indicates that human behaviour and the commitment to safety which are the underlying factors of human factors were the main reason for accidents identified by the participant, however, when the same participant was asked about the measures they have taken to avoid such accidents again and the participant responded with the better hazard recognition such accidents can be avoided as mentioned in his statement below;

> *"Yes, what I did is, I introduced a system called hazard recognition and what that does is that that is a step before the recognition of near-miss. So for me, if you recognize that there's a hazard then you can get them to report that before they report the near-miss". [SG-1]*

It can be perceived from the above statement that safety management should consider the human factor as an outstanding cause of accidents in order to avoid incidents on construction sites. Some construction safety practitioners do have an understanding of human error and they have mentioned human error as the cause of accidents but unfortunately, they have mentioned that there is no set process introduced in the construction industry yet to overcome human error.

> *"We don't have a system specifically, but the scenario we are looking at is increasingly part of that actually come out of where we have nuclear power stations where human factors is a big element and de-risking the processes and particularly that come out of that industry where there are operational issues. How somebody has reacted to the situation controls safety. But it does ripple out how workers have reacted to a situation on-site, staying focused and work processes and things. So we are considering that increasingly in the construction industry but we don't yet have a set process in place in a part of that. Our design management process at the moment makes sure that people are aware that is a significant aspect but we need to consider this as well". [SG-1]*

However, the behavioural managers who have been interviewed had more relevant knowledge of accident mechanisms and also had a clear understanding of how human behaviour causes accidents on construction sites. The narrations below correspond to their response to the accident causation question.

> *"I probably recall a few years ago whereby an individual had his legs broken by a tally handler. And you know terribly, the individual had placed himself in such a position. So you know if you get into a deep dive on this, uh, human behaviour. We have also changed the methodology in terms of the lifting of FIBC bolt bags that were part of the lifting activity, so the FIBC bulk bags were being lifted by the telehandler onto the back of the flatbed truck, and the individual who got injured was a banks-man". [SG-3]*

Moreover, they have also revealed that they have a system in place to manage the behaviour of the people working in the organisation. For instance, one of them when asked if they have a system in place to manage behaviour has responded that;

> *"Obviously a lot of focus is placed back onto the supervision for this activity, making sure that we have competent people who are actually out there supervising our work. We also ensure that the workforce is fully briefed on being able to work on safe procedures so effectively that if they're unhappy with a safe system of work without fear of retribution, they convert the work safe procedure to their supervisor. Who will investigate it and leave it to uphold whether their concern is legitimate or explain to them why the safe system of work is robust. coupled with that, we have a behavioural based safety program called PALS plan attitude, lead and share and everybody who attends our projects is briefed on this. And it's not just about safety that that is a key thing". [SG-3]*

The research participants have explicitly underpinned their understanding of accident causation in their experience and also, and accident investigation exploration has indicated how accidents correspond to their experience. H&S professionals in the industry with extensive safety experience are familiar with the outstanding factors affecting safety as well as know the mechanism of accidents. As aforesaid, the most prevalent factors highlighted by the participants are communication, commitment, attitude, safety awareness and human error. More so, the other factor specifically highlighted by behavioural managers was human behaviour. To overcome these factors, the participants have mentioned that precise risk assessment, commitment to safety and supervision, and behavioural alignment could help to manage these factors. The literature review carried out during this research has rigorously revealed that all these causes highlighted by the participants are associated with the human factor (Nawi *et al.*, 2016; Zahoor *et al.*, 2017; Franciosi *et al.*, 2019; Winge, Albrechtsen and Mostue, 2019; Khalid, Sagoo and Benachir, 2021).

These findings inevitably state that the construction industry has to consider a human factor approach to deal with the incidents on the construction sites. Although H&S professionals mentioned the proximal causes associated with the human factor, however, unfortunately, they are not familiar with the human factors and undoubtedly, do not know how to deal with the human factor. Thus the next section of the interview tried to approach the participants from the human factor and inveil their understanding of the human factor which the research explored as an utmost cause of an accident. Where necessary, they have also been briefed on the human factor to record their explicit opinion on it and also explore how to deal with the prevalent issue.

6.3.4. Human Factors in Construction Accidents

This study has revealed that the core reason behind accident causation in the construction industry is the human factor (Nawi *et al.*, 2016; Zahoor *et al.*, 2017; Franciosi *et al.*, 2019; Winge, Albrechtsen and Mostue, 2019; Khalid, Sagoo and Benachir, 2021). About 80% of accidents happen because of causes associated with humans, therefore, further study on the human factor is pertinent for this study. The literature review, as well as the questionnaire study also indicated the human factor as an outstanding issue in the industry, therefore, to validate and to get in-depth insight, the human factor has been discussed with the participants to validate the framework developed. Moreover, to validate the framework, a series of questions have been asked to the participants in this regard and the key findings have been validated based on which the framework has been established. Thus the participants have been asked about their opinion on the human factor and further inquired how in their understating this is relevant in accident causation. Most of the participants have exhibited a fair understanding of human factors and agreed that the human factor could be the root factor of causes they have highlighted for the accident. For instance;

> *"Yes it is a significant driver to the safety system. also the ageing factor, the working conditions and mental health. These are the significant causes of accidents in the construction industry. However, sometimes they are tested because sometimes we have loads of pressure from overseas workers and their communication as well as working style could be different". [SG-2]*

> *"Yes I do agree that human behaviour is the issue behind most of the accidents but it's not limited to that. It also involves multiple factors like behaviour, attitude, peer pressure, and competency". [SG-3]*

Another participant mentioned that the human factor comes into effect due to a number of reasons;

> "The main reason behind the accidents is human behaviour and I would say unconscious behaviour, in my opinion, is the main reason. People get used to seeing the hazards and when they, unfortunately, get used to seeing

hazards then they no longer become the hazard and therefore they don't see that risk moreover, they don't perceive the risks as they used to from day one. So there are a couple of factors from me so time versus repetition and environment versus individual potential are the factors". [SG-1]

"Yes, so you know if you get into a deep dive on the accidents, uh, its human factors". [SG-3]

Hence, retrospectively almost all of the participants agreed and related the causes they indicated for the accidents with the human factor. Among the participants the understanding of the human factor as mentioned before was different. Some related it to the worker's demographics, some to the behaviour and a few to the communication. However, they validated that the human factor could be the root cause of the accidents and must be tackled. Therefore, the research hereafter aimed to investigate the participants to validate the framework developed to manage the human factor. The participants were inquired to elaborate on human factors management in their knowledge and experience and illustrate if they have a system in place for human factor management. A response given by a safety consultant to this query has been listed below;

"There's no technique in specific, however, with effective supervisors and management, I think we manage the human factor. So it is not within my organisation, because we don't operate any critical infrastructure, what we do is, we do design elements, we don't take that liability on us, typically in construction what we do we develop a design process to say if there's a buildable design and that's sort of human elemental construction liability part and goes to just the operating various kinds of plants, cranes, infrastructure that got to interface or clash with.". [SG-2]

This indicated that the principal designers only deal with design for safety and make sure that a buildable design is carried out, however, in their understanding more of the accidents are the result of the construction process for which the contractor has to be liable. Similarly, others have also recorded their responses, a few of them are;

> *"So you probably know there are two approaches towards behaviour safety. There is a negative reinforcement of behaviour safety and the negative reinforcement of safety is when somebody makes mistake then you punish them by either giving them a fine or a penalty, on the other hand, the positive reinforcement towards behaviour safety is recognising when somebody is identified if something that has been done well or achieved something positive. Well in behavioural safety you always reward the people to appreciate them giving them positive feedback. You always start with the good thing, you always encourage the positive behaviour behind a safe action". [SG-1]*

Another one stated that;

> *"We don't have a system specifically, but the scenario we are looking at is increasingly part of that actually come out of where we have nuclear power stations where human factors is a big element and de-risking the processes and particularly that come out of that industry where there are operational issues. How somebody has reacted to the situation controls the safety. But it does ripple out how workers have reacted to a situation on-site, staying focused and work processes and things. So we are considering that increasingly in the construction industry but we don't yet have a set process in place in a part of that. Our design management process at the moment*

> *makes sure that people are aware that is a significant aspect but we need to consider this as well". [SG-1]*

These statements as well as the data gathered from the other participants have categorically directed that the construction industry lack behind in the safety management of other safety-critical industries. The human factor is considered a well-known cause of accidents in other industries but the construction industry relies more on traditional ways of safety management. So far, using the IPA methodology, the emergent themes in relation to the human factor management established by the research participants were; effective supervision, behavioural incentives and design management process. Subsequently, as seen before during the analysis, the safety behavioural managers illustrated more understanding of the human factor and also highlighted methods to manage the behavioural aspect of the human factor. For instance,

> *"Uh, in terms of looking at human factors as well, I mentioned our, uh, behavioural based safety program PALS. So we have supervisor training and getting them to look out in terms of… let me give you an example. An individual turns up for work who is highly competent but has had a nurse sleep because of maybe an argument with their partner baby crying, etc. and we train our supervisors to look for things like that. I mean, I, as you're obviously aware, the human factors can impact so adversely on human performance, it's unbelievable and you know it's kind of recognizing across our industry web. The practice there is looking at how we got and implement with our tasks and teams to ensure that, you know, we've got a robust manner of dealing with and looking at human factors". [SG-3]*

Similarly, another one stated that;

> *Yes, we do have a system called PALS. That is plan, attitude, lead and share. So that involves robust planning, the right people right attitude, leading by example, and sharing information. That is the systematic way, we have developed to manage the human factor. By managing the behaviour and attitude we can I think improve it. Also, we have a value-worth system everywhere in the organisation. For example, if you put more value into safety it's gonna worth more and if you don't put much value then you have not had a good outcome. So it's up to the top management which actually defines the value of safety or any other aspect of safety. The problem I think construction company has today is that its reluctant towards introducing new systems and new things for the betterment of the industry. So if we adopt value-worth that could have the industry significantly. [SG-3]*

This reveals that some construction companies do know the significance of behavioural management and they have established systems to promote good behaviour throughout their organisation for better performance. Specifically, the programs like PALS and Value-Worth have indicated how a few companies have approached the behaviour for the improved overall performance of the organisation. Unfortunately, the safety professionals in the construction industry did not portray an explicit and broad approach to safety management, instead, focus on the conventional methods. For instance, in response to the asked question, most of them revealed that communication, clear job description and effective supervision could help to mitigate the effects of the human factor. However, the previous research has highlighted the shortcomings of the traditional safety management systems and also found that the human factor is not limited to human behaviour but also involves other personnel and safety traits such as attitude, commitment, safety perception, knowledge, and communication which needs to be analysed before the construction process commences. Thus this research carried out through interviews has so far enlisted the following findings.

1. The participants have unanimously validated the current safety practices being practised in the UK construction industry.
2. As explored in the literature review, the current/traditional safety management constitutes a plan, do, act, and check cycle. Participants have mentioned that this process is embedded into the safety regulations which is usually carried out in the following order; design for safety, risk assessment, method statement, and supervision.
3. According to the participants the most prominent causes of accidents are; management commitment to safety, ineffective communication, understanding between management and operator, human error and human behaviour.
4. Moreover, one of the findings of this research is that safety is considered the sole liability of the contractor, therefore, is considered responsible for the accidents on the site.
5. Although most of the causes highlighted by the participants behind accidents correspond to the human factor, however, construction safety professionals are not familiar with the human factor and how the human factor triggers the accidents.
6. Behaviour managers in the construction industry relate accidents with human behaviour and they have mentioned that promoting good behaviour helps to reduce accidents.
7. The construction safety professional believes that with effective risk assessment, communication and supervision human factors can be reduced.

Hence these findings have indicated that the construction industry needs to consider the human factor aspect of safety management is found as the utmost cause of accidents. Unfortunately, the construction safety professionals revealed a limited understanding of the human factor and its management, thus, the next part of the research will validate the proposed framework which is based on two safety concepts ‘site risk assessment’ and ‘human error assessment' using immersive technologies.

6.3.5. Human Reliability Analysis (HRA) in Construction Industry

The analysis so far dealt with the validation of the first three objectives based upon which the framework has been developed. This section aims to validate the proposed framework and identify its appropriateness according to the participants. As aforementioned in Chapter 5, the proposed framework has been developed in two stages. The first stage involved the development of an immersive human reliability analysis model, whereas, in the second stage the framework for human factor management has been proposed based on established HRA. As the proposed framework has been developed explicitly on the research findings, therefore validating the research findings has been inevitable. The construct validity as explained earlier deals with the appropriateness of the research operationalization (Taherdoost, 2018). To put it another way, construct validity is involved in ensuring that an investigation is measuring what it is designed to assess in accordance with its stated goals. Therefore, construction safety professionals have been engaged to validate the appropriateness of the framework.

Although the proposed framework was developed based on the literature review and questionnaire study, however, for the research integrity and to ensure the appropriateness of its work for the construction industry the validation had an enormous significance. Thus several questions have been asked on human reliability analysis and human error assessment. Moreover, participants have also been inquired about immersive techniques for health and safety management and immersive safety training. For instance, the first question sought the participant's view of human reliability analysis (HRA) and its potential usage in the construction industry. A mixed response has been found among the participants on HRA and its usage in the construction industry. Few participants demonstrated their understanding, however, no evidence of its usage in the construction industry has been found. Most of the safety practitioners didn’t know about HRA and how it is carried out. For instance, below is some of the feedback from participants;

> *“I might be familiar with HRA but I haven’t used any specific methods in the construction. We don’t have that in our UK construction industry”. [SG-1]*

Another safety expert stated that;

> *“Yes, I am broadly familiar with that but we haven’t used that in the construction and also haven’t seen anyone using that in the construction industry”.[SG-1]*

Similarly, one of the safety consultants revealed that it might be the contractor's responsibility to carry out a reliability analysis, however, the consultant's role is to make sure the construction process is safe and buildable. For instance;

> *“So it is not within my organisation, because we don’t operate any critical infrastructure, what we do is, we do design elements, we don‘t take that liability on us, typically in construction what we do we develop a design process to say if there’s a buildable design and that’s sort of human elemental construction liability part and goes to just the operating various kinds of plants, cranes, infrastructure that got to interface or clash with”. [SG-2]*

However, one of the safety consultants stated that we have a process to manage human reliability by making sure that the staff working on a critical activity is vigilant and attentive.

> *“We do have the equivalent of that that all staff works adjacent to the high-speed network have to get the diabetes health, drugs and alcohol tests, mobility checks to perceive risks, Eyesight tests, hearing tests as minimum requirement as they are working in the risk environment”.[SG-2]*

This indicated that the concept of human reliability hasn't yet arrived in the construction industry although the construction industry is far more dynamic, complex and socio-technical than before. Moreover, the statistics have revealed the human factor as the cause of accidents but no practices have been developed in the construction industry so far to overcome the human factor. Behavioural managers on the other side explicitly revealed their familiarity and some understanding with HRA, however, the methods they mentioned were not entirely HRA methods and also, and they have also mentioned their concerns about adoption in the construction industry as shown below;

> *"Yes, we have a system called the RSSB system. It's a general human error framework that takes you through. Uh, call them, hold points if you will, uh, whereby it's root and tree analysis. Basically for human factors. Uh, I mean you know you. You can link it back Simplistically to the James reason model, can't you? The Swiss cheese on our most fundamental level? Uh, I mean and you know that at the very core principles. Uh, you know, underpin the way we look at our Accident Investigation, so you know, we go through whether it's human error, user interface, whether it's a component failure, whether it's an organizational failure so we have all of these sitting in our toolkit in the back. In the background, you know whether it's unsafe, supervision preconditions for unsafe acts and so forth and so on". [SG-3]*

Similarly, another one stated that;

> *"Okay. So we don't have that but we have a similar system in place that works the same way. We have a risk assessment of two kinds. So the first one is generic risk assessment and the other very important one is task-specific risk assessment. That is carried out on a system called ERIC which is*

> *eliminated, reduce, Inform and control. So that starts with identifying the risk, then using the ERIC approach to try to eliminate or reduce the risk then informing the site working and the last and very important is a control which is done by the supervisor".[SG-3]*

The systems participants mentioned do not explicitly analyse human reliability in the construction environment. However, when they have been told how HRA works the participant revealed the associated limitations as below;

> *"It is my hardest challenge unequivocally in trying to get embedments about exactly what you've spoken about in civil engineering and building. I will rail division absolutely gets this 100%. They understand the value it brings. But without discrediting civil engineering or building you take a step downwards in people's understanding and then they're not. They're not as mature, and I'm trying to embed this. I used, I've used previously something called dimensions of safety. Uh, and I've tried to embed this". [SG-3]*

The above argument and the statements by safety practitioners in the construction industry create concern about the construction industry being not mature and professional in adopting new methods and technologies. Moreover, it has been explicitly analysed by the participant's statements that the safety practitioners are reluctant to explore and adopt new methods to manage the outstanding issues. Similarly, the safety practitioners are strict in complying with the safety regulations and therefore are not familiar with the methods and techniques used in the developed industries of pertinent problems. Hence, the next part of the interview explored the immersive human reliability analysis.

6.3.6. Immersive Technology Implications in UK Construction Industry

Section 3.4 has explicitly reviewed various technologies being practised in the construction industry as well as critically analysed the limitations and impact of these technological interventions. The research findings steered the study to explore relevant technologies which can help to overcome the found shortcoming associated with the H&S. On reviewing several technologies being practised in the construction industry, this study found and opted to use immersive technology for the framework development due to several reasons which are as follows;

(i) Immersive technology has abilities beyond visualization and communication like many other technologies being practised in the construction industry. For instance, its ability to develop simulators is a significant advantage over other technologies that could help to develop Immersive HRA.

(ii) this study has revealed that human factors can be managed by influencing human cognition and conscience by identifying and quantifying human error through reliability and training. Immersive technology with its ability to develop the real environment that can help to quantify and assess human error possibility.

(iii) Other than many visualization technologies being practised in the construction industry; immersive technology provides a sense of spatial immersion, emotional immersion, cognitive immersion, and sensory immersion which can help to manage human factors (Khan *et al.*, 2021a).

(iv) It develops a safe and enriching learning environment for the users to carry out complex processes and procedures without getting involved in the associated risks (Loosemore and Malouf, 2019).

(v) With hands-on experience and expertise, immersive tools facilitate the development of virtual environments much easier and quicker than other modelling tools used in the construction industry.

(vi) Immersive technology has already been used in the construction industry for visualization and training purposes. The existing experience would facilitate the construction industry to implement the proposed framework.

As aforementioned, several scholars have penned on the implementation of immersive technologies in the AEC industry because of their vast applications in communication, visualization, and immersive capabilities. Freina and Ott (2015) carried out a systematic literature review on the application of virtual technology in the construction industry as well as elaborated on its significance in educating construction pupils. Khan et al. (2021) critically reviewed the immersive technologies application in the construction industry and highlighted its upsurge in the construction industry. Moreover, they further reviewed its vast applications in information sharing, collaboration, communication and visualization. Gopinath and Messner (2004) reviewed the potential use of immersive technologies for facility prototyping development for enhanced communication during the design and construction phases of a project. Similarly, many other researchers have reviewed the immersive technology adoption, acceptance, limitations and advancements in the construction industry.

The above literature review has presented the current involvement of immersive technologies that range from communication to information sharing, collaboration to visualization, and modelling to immersive training. Similarly, immersive technologies have also made their way to construction health and safety management. For instance, Afolabi, Nnaji and Okoro (2022) reviewed the potential use of immersive technologies for risk modelling in the construction industry. Similarly, Getuli et al. (2018) proposed a framework to introduce immersive technology in the construction industry. Nonetheless, the construction industry seems well familiar with immersive technologies, hence, encouraging the implementation of the proposed safety management framework. To further investigate the appropriateness of immersive technology for the framework development, the query has been raised to the interviewees and their statements have been recorded as below;

> *"We don't have this technology in our organisation but using the immersive technologies would be a significant advantage. For instance, immersive training can help significantly for designers and the construction community. Specifically for the designers nowadays don't have site experience, do they don't actually have the feelings for the things what they will look alike when it's being built or operated and also for the people working on sites they can actually perceive whats the site look a like and what conditions have will have to work." [SG-1]*

Similarly, another participant narrates that;

> *"We're running something similar on the railway where a camera is mounted to the front of the train. In a meeting and that is replayed back through something called the mission room, uh, the 4D model that allows you to walk through the infrastructure in a safe manner. Uh, but allows you to hazard, spot and pick up the hazards so effectively you taking you. You could do a, you could compile a risk register without actually having to need to be on the infrastructure. I mean, how amazing is that? [SG-3]*

Another participant also mentioned that;

> *"Yes we used a system called BIM in the past, we used that system to create risk assessments and method statements. The good thing with BIM is you can see mechanical and engineering construction clashes. You can add information from the BIM to the safety and risk assessment notes. It's a great visual aid for the workers you know it helps them to be in a safer workplace*

during the work. You can see where your workers are and where the risk lies you know." [SG-2]

The above statements illustrate the construction industry's familiarity with immersive technologies and a few types of immersive technologies that have been used in the construction industry. This also demonstrates that in the H&S domain, immersive technologies have been used for visualization, risk assessment and hazard analysis within the UK construction industry. Hence, the development of a safety framework will encourage the use of immersive technology as well as facilitate the construction industry to overcome safety issues in a more efficient and safe environment.

The literature review as well as the qualitative study has highlighted the key technologies that are being used in the construction industry. The technologies such as 3D and 4D dominate within the construction industry for planning, visualization, and risk assessment purposes. Many other notable technologies mentioned in the literature, are geographic information systems (GIS), immersive technologies, web-based safety management and monitoring technologies, digital technologies, and unmanned aerial systems (UAS) for safety management and risk assessment. However, the recent advancements in BIM, as well as immersive technologies, have equipped the industry with more options to improve deprived areas such as health and safety. The application of virtual and augmented reality technologies has also been evidenced in the construction industry, however, currently with no or little impact, especially in safety management. Undoubtedly, immersive technologies have the potential to conduct safety management with a more realistic and proactive approach as compared to other technologies.

The interaction of three elements; a computer, software, and peripheral hardware creates immersive systems Frank Moore and Gheisari (2019b). Symbolic practical application of immersive technology has been identified within the UK construction industry which is limited to the visualization or architectural aspects. However, this study has highlighted the potential use of immersive technology in the health and safety areas because of its potential to carry out real-time planning. The sense of realism or immersiveness is developed using a head-mounted display (HMD) devised and supported by software which integrates developed 3D space with HMDs. In the construction industry, the immersive environment is developed utilizing modelling tools such as AutoCAD 3, Revit, 3D Max, Maya or Blender followed by the game engine which is where most of the development is carried out to create a realistic environment by incorporating several functions to resemble the real world. This stage of immersive tool development has not yet started in the construction industry as it involves game engines and coding experience to develop associated with artificial intelligence. Unity 3D and Unreal Engine have been explored during this study which has the potential to develop an immersive HRA tool using the proposed framework.

6.3.7. Immersive Human Reliability Analysis (IHRA) Development

The previous section has indicated that the construction industry is not much familiar with HRA methods which this study has also explored through the literature review as well as through the questionnaire research. Thus the previous section has also validated the research finding, however, this section validates the development of the immersive human reliability model which has been developed in Chapter 5 based on the research findings. Literature has categorically highlighted the catastrophic effects of human error causing about 80% of accidents in the construction industry. This research then explored the human reliability analysis (HRA) as a human error management technique used in safety-critical industries through an extensive literature review. Therefore this study presented the idea of human error assessment through immersive human reliability analysis as the conventional HRA methods couldn’t make their way to the construction industry either because of their complexity, reluctance to adopt new techniques and technologies, industry’s behaviour and maturity.

Chapter 5 has explicitly stated the development of IHRA for the construction industry based on a few key parameters. The conventional HRA methods operate on identifying the human error probability (HEPs) using personal influencing factors (PSFs) which this study has explored as Human Factor Attributes. Thus the proposed IHRA has been developed based on the same principles of identifying human error probabilities using personal influencing factors (PIFs), however, in an immersive environment. Afterwards, the analysis of PIFs in the immersive environment has been explored in the previous research specifically in the questionnaire survey. Thus the research has found human actions, risk perception, hazard awareness, safety knowledge, communication and time as the measures of PIFs that determine the human error probability. Therefore, validating the personal shaping factors has been a key aspect of this section. The participants have been asked some situational-based questions to record their underlying understanding and feedback on the human error probability assessment in an immersive environment.

To validate human reliability analysis using PIFs, the participants were asked how human error probability can be assessed in the immersive environment. Quite intriguing answers have been recorded on the idea of immersive human error assessment and participants have been quite welcoming and interested to adopt this approach to safety management. For instance,

> *"Wow, that is very interesting, if you imitate the real situation you can assess through human actions, the way he acts and risk assessment. I never thought of it but this would be something a gamechanger in the industry. I would be very interested to do that. It's again the same thing. Value-worth. Now you are putting a value on safety and yes the outcome would be better. And I think that's very much possible if you can do the simulation. It's actually the opposite of our ABC model. Now in the immersive technology, you have CBA*

which means you can show the consequence that will influence the behaviour and would help to promote positive behaviour". [SG-3]

Similarly, other participants have found this fascinating if achievable.

"Yes, It would help as you can see if the person is identifying the hazards and risks clearly or not. Based on his actions you can assess his reliability. so you start doing the simulation exercise which would also help them perceive what actual environment they will be working with. This can help to evaluate the workers' error probability and also unsafety conditions on-site. So it has two major sides which can help the construction significantly". [SG-1]

Another one stated that;

Yes, I think we probably could. What you talking about is job profiling, if you profiling and seeing if you need a driver for an excavator and see what kind of skill, experience, age, and sharpness you require which I think you could. I am not sure about the expert level you are talking about. But if we can simulate a real site situation then it's very much possible and it's the same as doing the risk assessment. [SG-1]

Similarly, another one stated that;

"It will 100% improve it and test you could do which is very similar to that. let's not simulate the construction activity. There's been a lot of research on drivers. Forget construction activity which is a basic activity all the works would carry out. It's how to do the drivers in the motorway, the perception of the highway changing and their reaction to red-cross and other things that happen on sides. Now, there's an issue about people perceiving the risk

> *differently so they might react to it. So you got variants in there that you don't necessarily know how trained a person gonna be, what their perception is, how they would react. That I think would improve it. Because basically if you see a problem and you are able to visualize it for a site worker, it very unlikely that people will make the same mistake twice".[SG-2]*

Similarly, many others have elaborated their thought to support this concept and validated that human actions in an immersive environment could help to assess the error probability. This indicated that analysing human actions can significantly and risk perception, safety knowledge and other PIFs measures could help to analyse human reliability which validated the development of IHRA shown in Figure-79.

6.3.8. Immersive Safety Framework Validation

The last section of the interview addresses the validation of the proposed safety framework that has been developed on certain parameters to rectify the underlying causes of accidents. For validation; the developed framework was revealed to the participants. The significant parameters found through comprehensive research were (i) risk assessment, and (ii) human error assessment. The human error assessment has been addressed by the development of IHRA which has also been validated in the previous section. However, for environmental risk assessments, many techniques and technologies are being used in the construction industry of which BIM is well renowned. The conventional safety management systems circle around this risk assessment, however, the robustness of the proposed framework involves the consideration of human error mitigation along with site/environmental error mitigation. It has been revealed in the research that construction professionals are quite familiar with immersive technologies and a few immersive applications specifically for training purposes have been carried out by a few top construction companies. Therefore, this section has addressed the questions of risk assessment and training in an immersive environment which has unanimously been validated by the safety practitioners as this concept has already evolved in the construction industry. For instance;

> *"Yes, that we are looking to do increasingly. I was part of the working group of health and safety executives to build the health and safety initiatives and as a business, we do build BIM-based H&S design and management processes and I do believe that should be possible to identify the unsafe conditions on the sites and we should have people identify the hazards". [SG-1]*

This indicated that the construction industry is aware of risk assessment using visual technologies like BIM. Another participant also narrated the use of visual technology for risk assessment of the site.

> *"We're running something similar on the railway where a camera is mounted to the front of the train. In a meeting and that is replayed back through something called the mission room, uh, a 4D model that allows you to walk through the infrastructure in a safe manner. Uh, but allows you to hazard, spot and pick up the hazards so effectively you taking you. You could do, you could compile a risk register without actually having to need to be on the infrastructure. I mean, how amazing is that?". [SG-3]*

The proposed framework has also recommended immersive training for robust safety management. The last question of the survey, therefore, illustrated the viability of immersive training to improve safety performance as well as manage human error. Participants have unanimously been fascinated by the concept of immersive technology to improve safety performance. Some construction companies have been successfully using immersive training for improved safety management. The feedback from a few of the participants on this question has been listed below;

> *"100% I agree with that. But as I have said, my issue is if it doesn't relate to the actual activity then it's a very different test. So for example even if you visit the site on google maps, the google map is one year late then what you got is you then going into an environment that is not similar to when you have VR trained". [SG-2]*

> *"Yes absolutely. That is something that could help to reduce the incidents in the construction industry".[SG-3]*

> *"Yes, that would be helpful because it means they can make mistakes without any consequence in the immersive environment and can learn from them".[SG-1]*

6.4. Examination of the Findings

The core part of the safety management system in the UK construction industry is the Construction Design and Management Regulations (CDM) which bounds the stakeholders to carry out safety management at all levels of the construction project. From a broad perspective, the safety consultants working along with the principle designer carry out the safety during the design stages to make sure the safety of the structure as well as ensure the buildability of the structure safely. Moreover, the safety consultants use the design for safety (DFS) approach to ensure safety during the construction phase. However, the contractor is responsible for the safety of the construction activities during the construction phase. Thus the contractor usually has a designated safety department to manage safety during the construction process. A number of safety experts from construction companies have been interviewed to explore the safety practices in their organisations. Hence, similar safety cultures and safety practices have been identified across all construction organisations. However, human behaviour, according to behaviour managers, is the primary driver of safety, and safety performance can be enhanced simply by supporting good behaviour throughout the organisation.

In response to identifying the overwhelming causes of accidents, participants have explicitly informed their views on accident causation. Construction safety practitioners have identified several causes of accidents in light of their personal experiences. Moreover, the participants shared their experiences with the recent accidents they have encountered and mentioned the causes they found by accident investigation. The prominent causes of accidents identified were human error, personnel behaviour, miscommunication, attitude, and risk perception. An intriguing fact identified by the research is that construction safety professionals are not familiar with the human factor and how it affects safety at the site. All the causes identified by the construction safety managers are related to the human factor which this research has found as a key factor affecting H&S. On the other side, behavioural managers have mentioned the human factor as one of the reasons for the reduced performance in the construction industry.

The proposed framework has also been validated through semi-structured interviews carried out in this research. This has been achieved by validating the core principles used for the development of the framework. For instance, the participants have been inquired to review human reliability analysis (HRA) which is the method used in other industries for human factor management and its potential usage in the construction industry. Only a few participants showed their understanding of HRA, but no proof of its use in the construction sector has been discovered. Thus the proposed framework has been validated by the explicit discussion on human reliability analysis and risk assessment utilizing immersive technology. The participants have not only unanimously agreed and validated the framework but also appreciated the concept to improve safety management in the construction industry.

This research further highlighted that the concept of human reliability has not yet arrived in the construction industry, despite the fact that the construction industry is far more dynamic, complex, and socio-technical than it was previously. Although statistics have revealed that the human factor is the cause of accidents, no practises overcoming the human factor have been developed in the construction industry thus far. The emerging themes from the interviewees have endorsed the development of immersive human reliability from two perspectives namely risk assessment and human error assessment in an immersive environment. Moreover, the other emerging themes recorded in this research have been shown in Figure 6.1 which demonstrates the validity and reliability of the qualitative research as well as validates the framework development.

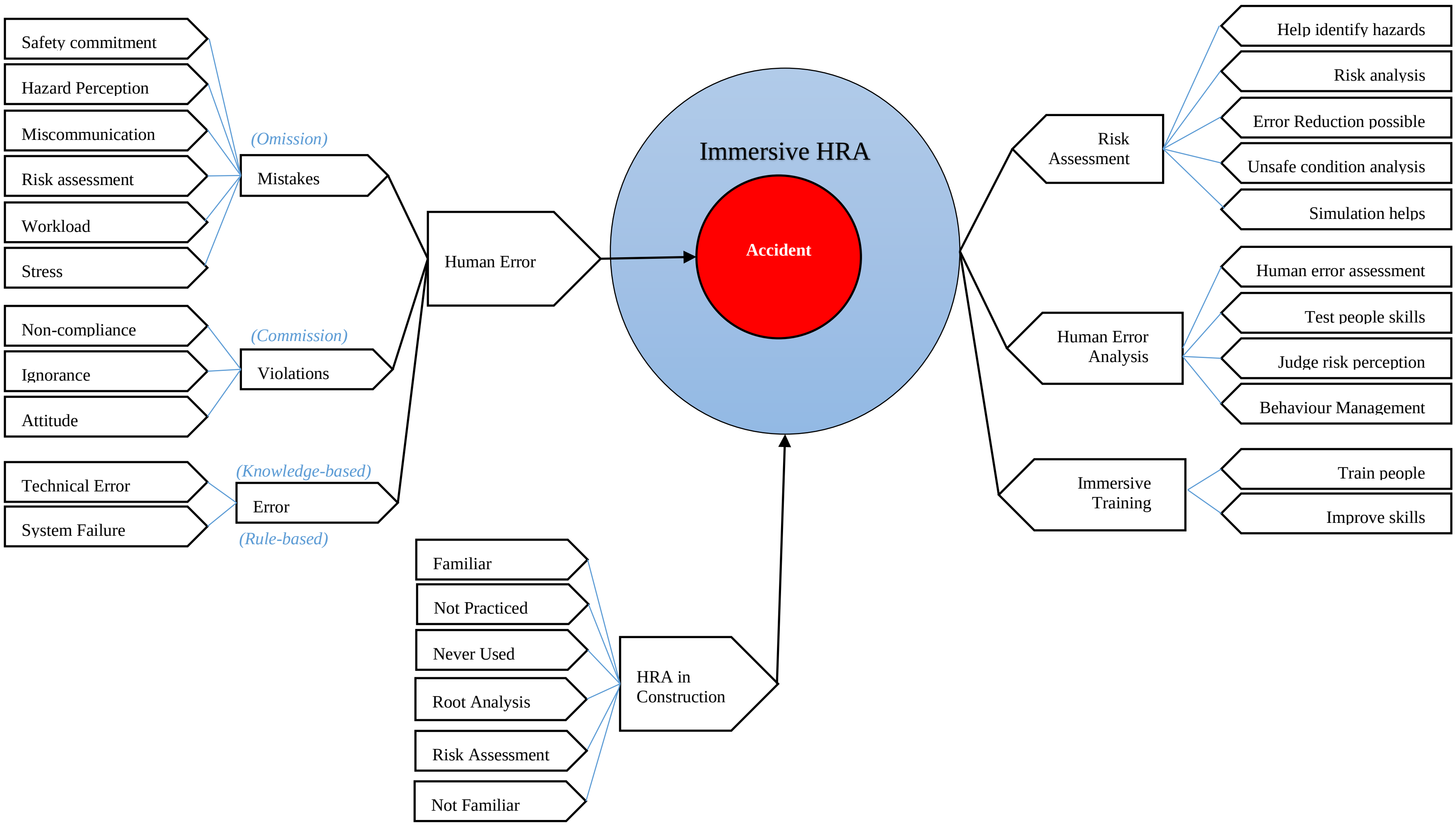

Figure 6.1: Emerging Themes from Qualitative Research

6.5. Chapter Summary

The qualitative analysis carried out in this chapter validated the proposed H&S framework as well as revealed several significant findings on H&S management in the construction industry that can be used to draw some conclusions. Interpretative Phenomenological Analysis (IPA) was identified and employed as the most appropriate method for the analysis of semi-structured interviews conducted by the H&S practitioners in the UK construction industry. Each research objective has been addressed and required to validate the development of the proposed framework. Starting with validating the causal factors involved in the initiation of accidents in the construction industry and followed by exploring the HRA methods to rectify and mitigate the overwhelming factors, this chapter took in-depth insight into safety issues with the safety experts to validate the research findings. The research has identified that the construction is old-fashioned and needs enormous improvements in safety practices to deal with the current challenges more dynamic complex and socio-technical industry. A detailed discussion of the participant's feedback has been carried out in Chapter 6 to validate the research outcomes that validated the proposed framework. Each objective has been validated through the rigorous discussion of safety experts to validate the research findings and the framework has been validated using the construct validity approach. A thorough discussion of the participant input was held to confirm the research findings, which validated the proposed framework.

Chapter 7: Conclusions

7. Introduction

This chapter summarises the study's main findings, conclusions, and contributions. Furthermore, the chapter discusses the study's conclusions and achievement of the research objectives in order to highlight the study's contribution. The study's limitations are also discussed. Finally, the chapter concludes with potential research contributions for future research based on the study's findings and limitations.

7.1. Synthesis of Research Objectives

The study set out to develop a novel framework to eliminate the accident causal factors for robust safety management using advanced technologies to improve the safety performance of the construction industry. Followed by the explicit review of safety causal factors, their impacts on performance as well as prevailing methods have been presented in Chapter 2. Subsequently, the comprehensive review of prominent factors affecting safety management has been highlighted and the methods used in safety-critical industries have been explored in Chapter 3. The rigorous research in Chapter 2 and Chapter 3 has identified human factors as the overwhelming factors causing around 80% of the total accidents in the construction industry. Moreover, Chapter 3 meticulously explored the methods and techniques used in safety-critical industries to manage human factors and details a discussion on adoption and limitations in the construction industry has been steered. Additionally, a questionnaire survey was conducted to get input from the safety experts in the construction industry on the above finding. Based on the established findings, a framework has been proposed in Chapter 5 which has been validated through semi-structured interviews in Chapter 6. The successful accomplishment of the derived objectives for this study has been illustrated in Table 7.1 below.

Table 7.1: Summary of achieved research objectives

Sr#	Research Objective	Achievement	Method Used
01	Determine through the literature review the current H&S performance, practices, improvement efforts in the UK construction industry.	Insight into H&S in the industry Chapter 2+5	A comprehensive literature review research have been carried out on UK construction safety performance, and prevailing practices used in the UK construction industry.
02	Undertake a critical review of the impact of safety causal factors on H&S management and determine the key factor that contributes to accident causation.	Explored key H&S issues Chapter 2+3	A rigorous literature review has been conducted to determine the factors affecting safety management in the UK construction industry. Empirical research based on the study of one hundred and one articles has figured out around sixty factors affecting safety management.
03	Explore through literature the impact of those factors and remedial current methods/techniques as well as the advanced immersive technologies to overcome the issue.	Data Collection & Analysis Chapter 3+5	Extensive quantitative research based on thirty-four questionnaire surveys have been carried out targeting Health and safety professionals within the UK construction industry to get their input on the research questions.
04	Conduct the qualitative research to get the construction H&S professional input to strengthen the research questions.		
05	Develop a framework aiming to eliminate those factors from the construction process by utilizing immersive technologies.	Framework Development Chapter 5	Safety Management Framework has been developed based on the findings of objectives 1-4.
06	Validate the framework and evaluate the appropriateness of the framework by developing a research instrument and concluding the research.	Research Validation Chapter 6	Framework validation has been carried out through semi-structured interviews conducted with lead safety experts within the UK construction industry.

This study used a literature review and data collected through a questionnaire survey and semi-structured interviews within the UK construction industry to develop a safety management framework. This involved carrying out a comprehensive literature review throughout the research journey, safety documents analysis, and accident investigation studies. Moreover, 34 questionnaire surveys have been carried out to develop the framework followed by 20 semi-structured interviews to validate the proposed framework. The following sections summarise and present the key findings associated with each objective.

7.1.1. Objective 1:

Determine through the literature review the current H&S performance, practices, and improvement efforts in the UK construction industry.

The first objective needed to formulate a comprehensive and coherent understanding of prevailing health and safety practices and performance within the UK construction industry. This objective has been achieved through a rigorous literature review that established the major determinants for investigation, for instance, the health and safety performance industry of the construction industry, causal factors affecting safety performance, and identification of compelling safety factors causing most of the accidents through accident investigation. This review helped to identify the knowledge gap and set out the direction to carry out the pilot study targeting safety experts through a questionnaire survey. That eventually encapsulated the research findings for the development of a safety management framework.

This objective enabled this research to review and comprehend existing knowledge on H&S practices, weaknesses, and factors that affect safety in the construction industry. It also paved the way for this study by identifying research gaps and helping in the development of a safety framework. Furthermore, this objective has been achieved in Chapter 2 by comprehensively reviewing the state-of-the-art literature and HSE reports on construction performance and underpinning the effects of safety on overall construction performance within the UK construction industry.

7.1.2. Objective 2:

Undertake a critical review of the impact of safety causal factors on H&S management and determine the key factor that contributes to accident causation.

A systematic literature review process has been carried out to investigate the factors affecting safety management. This involved empirical research techniques to review more than two hundred articles to encapsulate the list of factors affecting safety management cited by the researchers investigating safety causal factors in the construction industry. As a result, a list of about sixty influencing safety factors has been developed and causal factors have been categorized into six categories namely; managerial, organisational, legislative, social, environmental and personnel factors. Additionally, based on these findings a framework has also been proposed to manage each of these factors at different stages in the organisation. These causal factors including the framework were later published in a reputed safety journal through an article that has been included in the appendix. Thus, these findings didn't only provide the foundation to further develop the research but also envisaged the route to investigate the construction industry's input on identified safety influencing factors.

7.1.3. Objective 3:

Explore through literature the impact of those factors and remedial current methods/techniques as well as the advanced immersive technologies to overcome the issue.

Followed by the documentation on safety influencing factors, the research further aimed at exploring the impact of those factors to identify the most influencing factors causing most of the accidents. This objective has been successfully achieved in Chapter 3 by an in-depth review of accident investigation studies found in the literature. Accident causation models and theories have also been reviewed meticulously to identify the notable safety factors causing most accidents. These, personnel/human factors have been identified as the most prominent factors causing about 80% of accidents in constriction and other safety-critical industries. Subsequently, this objective also aimed to examine the prevailing methods/techniques used to manage the substantial factors that this research explored as human factors.

The comprehensive literature review has found the human reliability analysis (HRA) method as an effective technique used in safety-critical industries to eliminate human factors. Several HRA methods have been reviewed; their historical development and operating method have been extensively discussed in Chapter 3. This research further investigated the potential use of HRA in the construction industry, however, little evidence of HRA use has been found in the literature due to several limitations discussed in Chapter 3. The complexity of HRA methods has been found as the prominent reason for limited or no use in the construction industry. Furthermore, immersive technology has been identified as a useful technology for mitigating human factors through immersive training and analysis of human reliability.

7.1.4. Objective 4:

Conduct Quantitative research to get the construction H&S professional input to strengthen the research questions.

The next phase towards the development of the safety framework was a quantitative study carried out through a questionnaire survey targeting safety professionals within the construction industry. The questionnaire survey has been one of the most important strategies used in this study to strengthen and validate the research outcomes so far. The questionnaire study conducted in this research sought safety professionals understanding of the research questions as well as investigated their knowledge of accident causation, factors affecting the H&S, human reliability analysis (HRA) and their feedback on the application of immersive technology to eliminate the causal factors. To gather participants' perspectives on the causes of the accident and human reliability analysis (HRA); an online semi-structured questionnaire for health and safety professionals was developed in three sections. Based on the participant's expertise, the questionnaire obtained extensive knowledge of health and safety issues, safety procedures, and detailed explanations on how to mitigate the issues.

The questionnaire survey not only validated the previous research findings but also established novel knowledge required for the development of the framework. Following the literature review process, the questionnaire has also been separated into three sections each focused on prevailing safety practices, accident causation, and lastly participant's knowledge of the human factor and remedial methods. Human error was identified as the root cause of construction site accidents by 60% of the participants, validating the literature study. Other prominent factors were technology, complex sites and inadequate systems/standards. Moreover, as revealed by the literature unsafe human action lead to human error that causes accidents on construction sites. Followed by section-3 of the questionnaire survey seeking safety experts' opinions on HRA. Very limited evidence of HRA usage in the UK construction industry has been found however, participants have greatly agreed that immersive human reliability analysis and immersive training can be helpful to reduce the impact of human factors.

7.1.5. Objective 5:

Develop a framework aiming to eliminate those factors from the construction process by utilizing immersive technologies.

Objective 5 has been achieved through the development of a framework, following the literature analysis and the questionnaire investigation. The process was to ensure that the issues raised were captured and the proposed framework was improved based on expert intervention. Thus the study's aim has been achieved in the objective by fulfilling the gap found the in preceding objectives. Thus a robust framework has been proposed for the construction industry specifically for the contractors to manage safety during the construction phase of the project. Furthermore, the proposed framework is based on HRA techniques which this study has rigorously examined as an effective technique to manage human factors, however, unlike traditional HRA methods, this framework utilises immersive technology. Hence, the framework is aimed at helping the industry in assessing the safety behaviour, risk perception and hazard awareness of the construction workers and rectifying the weakness with tailored immersive training.

7.1.6. Objective 6:

Validate the framework and evaluate the appropriateness of the framework by developing a research instrument and concluding the research.

One of the significant phases of this research was to validate the appropriateness and working of the proposed framework and research outcomes from the safety expert perspective. Thus, semi-structured interviews have been carried out with safety leads and behavioural managers within the UK construction industry. Subsequently, qualitative data analysis using the interpretative phenomenological analysis (IPA) technique has been used to analyse the results of the interview and validate the framework. Interviews have been conducted with lead safety and behaviour experts within the UK construction industry. The IPA regards a person as a cognitive, linguistic, and social being, and assumes a chain of connections between people's speech and their emotional responses, thereof, selected as an appropriate technique for the research validation.

Following the literature review, a semi-structured interview has been structured in phases to evaluate each of the research objectives to validate the framework. As the proposed framework was established on the first four key objectives thus the validation is required to verify each of those objectives from the respondent's outlook. The respondents validated most of the research findings, however, distinctive opinions have been identified between the safety experts and behaviour managers on human factors. Some linked it to the workers' demographics, while others linked it to their behaviour and a few to their communication. However, the behavioural managers illustrated more understanding of human factors in accident causation and also highlighted methods they have in place to manage human factors in construction organisations, on the other hand, safety professionals rely more on prevailing safety practices. Similarly, safety professionals in the UK construction industry showed limited knowledge and understanding of human reliability analysis (HRA), however, did agree with more of the research findings and hence, validated the proposed framework.

7.2. Summary of Key Research Findings

The key findings of this research are listed as follows;

- One of the key areas of research in this study was identifying the proximal and distal factors affecting safety in the construction industry. Extensive systematic research has been carried out using Nvivo software. Moreover than one hundred articles focused on safety factors have been screened in this research to encapsulate a list of potential factors affecting H&S within the UK construction industry. The research successfully identified as well as categorised more than sixty potential safety factors and categorized them into six H&S clusters namely; organisational, managerial, legislative, social, environmental and personnel factors. Moreover, a framework has also been developed to manage the potential factors by identifying the safety components, elements and drivers at the organisational level. Additionally, an article has also been published out of this part of the research in a prestigious top-ranked Q1 journal (see Appendix III).
- In pursuit to explore the proximal factors, personnel/human factors have been found to have a more drastic impact on safety within the construction industry. Thus an in-depth study of human factors based on accident causation models and theories has highlighted human actions and human errors are the prevailing reason that initiates accidents. Furthermore, the study also identified human behaviour, risk perception, hazard awareness, safety knowledge, working attitude, and experience as the causes of

inappropriate human action or human error during work also known as ‘human factor attributes’ and ‘performance shaping factors.

- Human reliability analysis (HRA) has been discovered as an effective technique that is widely utilised in safety-critical industries as a systematic technique for identifying, quantifying, and mitigating human error in complicated safety systems. In various industries, this strategy has been utilised successfully to control the personal characteristics and behavioural features of workers in a human-machine system. The intricacies of these methods have been cited as one of the major reasons why they have not found their way into the construction industry. Furthermore. the construction safety professionals underpinned HRA methods to manage human factors considering complexities to be avoided.
- Technological advancements have helped the construction industry in many fields, especially in design, planning, and monitoring. However, safety management has not fully yet benefited from the advancements in technology and relies mostly on traditional bureaucratic procedures to comply with the regulations. This study investigated cutting-edge technologies utilised in construction and discovered that automation, visualisation, and immersive technology are among the top trends in the construction industry. This research discovered that immersive technology has significant potential to develop immersive human reliability analysis because of its immense applications in training and education.
- Based on the above findings, an immersive safety management framework has been proposed which has been validated using qualitative interpretations. Validation has been done by interviewing construction safety professionals and behaviour managers considering the behavioural aspect involved in the human factors. The safety professionals revealed a limited understanding of human factors as well as human

reliability analysis (HRA). On the other hand, behavioural managers have illustrated some understanding of human factors, their mechanism and their impact on safety management. However, based on the comprehensive discussion of the research findings and data analysis, the respondents have validated the proposed immersive safety management framework.

7.3. Key Research Conclusions

The key conclusions drawn from this study findings are as follow;

- The study explored some of the insights into safety management in the UK construction industry. The performance of the construction H&S has been found unsatisfactory with the fatalities rate one of the highest in the country. According to the findings of the study, the construction sector is deemed to be outdated and requires massive improvements in safety practices in order to deal with the current problems of a more dynamic, complex, and socio-technical industry.
- The prevailing safety practices comprise complying with safety regulations, however, the research found that more inclusive safety practices are required to deal with the current safety challenges of the construction industry. Furthermore, the deficient safety practices in the construction industry do not respond to all the factors affecting safety management. This highlights the importance of innovation and development in the field of safety management in the construction industry.
- The research has brought up a few interesting facts about the key causes of human errors in the complicated socio-technical system. The rigorous literature study carried out at the early stages highlighted the root causes of accidents which have been validated not only by safety professionals but also by peer reviewers at the top safety Q1 journal (see Appendix III). The key causes identified by the research were; human errors, technology, complex sites, and inadequate systems/standards. However, the

significant weight has been occupied by human errors that lead the research towards human traits causing most of the accidents.

- Taking into account human traits as the undisputed causes of incidents in construction sites. This research has further revealed that human factors as an area of great concern, especially in the safety management domain. Through extensive research, human factors have been found as proximal factors contributing to the significant amount of accidents in the construction industry. Construction safety professionals have shown mixed understanding of the human factor and its contribution to accident causation as found in the literature. Few of the respondents specifically construction safety managers endorsed the system thinking of dealing with the safety issues, however, other respondents mostly behavioural managers advocate for the personal engagement and feedback system to deal with safety management.
- One of the explicit findings of this research was the reluctance of the construction industry in adopting new methods and technologies. The research found that the safety professionals in the industry rely on conventional methods for safety management and are not open to innovation to deal with the advanced challenges in more socio-technical complex industry needs. Moreover, while other industries have been adopting a system approach for safety management; the construction industry still holds the contractor as the sole responsible for safety management.
- The research further examined the techniques and methods used in safety-critical industries for managing human factors to overcome their drastic impact on the construction industry. Human Reliability Analysis (HRA) is identified as one of the useful methods that have a long history in managing the human factor in many industries, however, it could hardly make a limited impact in the construction industry due to several reasons, for instance; the complexity of methods, resistants nature of

construction industry and the unwillingness of construction professional to deal with safety issues. HRA reflect a systematic strategy for identifying, quantifying, and mitigating human error in complex organisational processes.

- However, in terms of the application of this method, this research revealed that the concept of human reliability analysis has not yet arrived in construction, even though the construction sector is significantly more dynamic, complicated, and socio-technical than it was previously. Although the statistics have proven that humans are a significant contributor to accidents, however, no strategies to overcome the human factor have been devised in the construction business thus far. Behavioural managers, on the other hand, directly indicated their acquaintance and some understanding with HRA; yet, the ways they mentioned were not wholly HRA procedures.
- Further on the identification of potential methods for human factors management in the construction industry through a succinct literature review, the idea has been presented to the safety professionals in the construction industry to discuss their understanding and possible usage in the construction industry. The idea was appreciated by the safety professionals and around 73% of the respondents agreed in the favor of human reliability analysis approach, however, as previously mentioned few concerns have been raised and the most prominent among them was the complexity of these methods and the involvement of human factor specialist involvement.
- The idea was then further established by the introduction of immersive technology to develop convenient and user-friendly methods for HRA. Immersive technology has been selected after exploring several technologies being used in the construction industry. It has been found that immersive technology best suit the purpose because of the sense of immersion and carrying out the human error assessment in the virtual environment. It has been established by this research that human reliability analysis can

be carried out by assessing human factors attributes/performance shaping factors (PSFs) in the immersive environment.

- The above findings facilitated the research to propose a framework for immersive human reliability analysis. The proposed framework follows the same mechanism used in the conventional HRA methods, however, instead of relying on complex calculations or expert opinion, the proposed framework gives the opportunity the safety managers to use immersive technology to identify the potential risks and hazards on construction sites as well as to conduct human error assessment in the immersive environment. Furthermore, the research further adds the importance of immersive training that this research found conducive to avoiding human errors.

7.4. Research Limitations

There are always some limitations associated with every research so do this thesis. Thus the main limitations associated with this study are as follow;

- The systematic research conducted in Chapter 2 is entirely exploratory carried out through a literature review, and the recommendations made in the research do not deny or replace any of the existing practices in the industry. Furthermore, the data collection had been performed from the construction literature, therefore, the outcome only relates to construction safety management. Hence, the study should be regarded as a contribution toward the safety knowledge that can help the construction industry to determine how safety is planned and executed and what factors are involved in the improvement of safety performance. Therefore, the author recommends future researchers use this study as a proposal for testing the framework and determining the extent of improved overall safety outcomes and performance.
- The careful review of the survey respondents used as the primary research tool reflects that the most of respondents belonged to either infrastructure or commercial

backgrounds. The respondents from the residential construction sector were not part of this research.

- Since the study was based on the opinions of safety experts and professionals from UK construction companies, the findings may be peculiar to UK safety management.
- One of the main limitations of this study was the lack of technical knowledge/expertise in the area of immersive technologies. The validation of the proposed immersive human reliability framework could have been extended to the application of immersive technology to the proposed framework, however, due to limitations the validation was limited to the professional interviews only.
- The engagement with research participants has been a significant issue faced during the research because of the Covid-19 pandemic. The research validation which involved interviews was affected because of the pandemic and thus limited engagement has been achieved. Instead of face-to-face interviews; the engagement has been made through online face calls or on the telephone. Moreover, it also affected the number of respondents which could have been increased in a normal situation.

7.5. Contribution of Research

This research contribution can be categorised into two different aspects; (i) Theoretical contribution, and (ii) Industrial contribution. The first aspect looks into the theoretical contribution of this research, whereas, the second one addresses the practical implications. Each of these aspects is discussed below;

7.5.1. Impact on Academia

This study provides empirical support for propositions made in the literature on the key factors affecting health and safety in the construction landscape. It further highlights the area of significant concern regarding H&S application in the complex socio-technical industry. Moreover, this research has contributed enormously by exploring the relationship between accident causation and related factors. Before this study, limited evidence on the key determinants of accident causation have been assembled by researchers in the construction field. The focus of this study has been on determining the key safety factors behind the H&S issues in the industry to propose a practical solution. This research, therefore, categorised the key determinants of H&S through a systematic literature review which has been later validated by the safety experts. The key academic contributions of this study have been summarised below;

- The systematic empirical research highlighted the key factors affecting health and safety management and a framework has been developed to manage the pertinent factors at the different organisational levels (this research has also been published). This will not only allow academia to further extend this research but also the industry to manage potential factors which could cause incidents on construction sites.
- This study aimed as well as explored the main cause of accidents in the construction industry, the shortcoming of conventional methods, and technological interventions in the industry. This provides future researchers with an opportunity to further develop this study rather than starting from scratch.
- Additionally, one of the main contributions of this study was to highlight the relationship between workers and accidents. Human factors have been the significant concern analysed in this study that illustrated the direction for future research in the H&S domain in the construction industry.

7.5.2. Impact on Industry

This research set out to highlight the area of concern within H&S management in UK construction and propose a solution to improve the overall performance of the construction industry. Thus, a pragmatic approach has been adopted to address the H&S issues within the construction. Therefore this research has benefitted the construction industry by developing a novel framework for robust safety management. The proposed framework has equipped construction professionals to analyse the worker's reliability in the immersive environment as well as provide immersive training to improve safety performance. This research has explored safety practices and tools being practised in the construction industry. It has been evidenced that the UK construction industry heavily relies on basic 2D and 3D tools for safety management and has not yet fully benefitted from immersive technology specifically in the H&S domain. Therefore, this study does not only highlight and promote the potential usage of immersive technology in dealing with H&S issues, however, but the proposed framework also illustrated the essential steps required to develop as well as analyse human reliability and carry out the immersive training for the critical activities. This immersive safety package will facilitate the construction industry to overcome the socio-technical and complex safety issues using real-time immersive technology which otherwise will not be possible to perceive using contemporary technologies. Therefore this study provides an effective and advanced tool to the construction industry to improve H&S performance in the UK construction industry.

7.6. Research Recommendations

- This study has successfully explored the prominent causes of accidents in the construction industry and developed the framework to mitigate the impact of those causes. As the proposed framework has been established to help site workers to establish safety knowledge, understanding as well as behaviour in an immersive environment before going to the actual site. Consequently, future researchers could explore how the proposed framework is aligned with offsite workers engaged in the planning or design phases of the construction projects.
- Whilst this study focused on developing a framework to improve safety management in construction, future research could go beyond this level towards further refinement of the framework by developing immersive tools based on the proposed framework.

This would provide the construction industry with a more effective tool to deal with the current and developing safety challenges in a more complex socio-technical industry.

- Considering the high fatality rate in the construction industry, priority should be given to safety management by researchers to develop more effective tools and methods to address the current needs of the industry. This study has explored that safety is usually given the least priority in the construction industry, this could be considered by future researchers by introducing more introducing systems approaches to safety management.
- Lastly, this research used a literature review and questionnaire as primary data to propose the framework, the future researchers are recommended to conduct action research on the core issues of safety in the construction industry that encourages safety professionals to take part in developing systems and methods to improve safety. In doing so, this study's findings could act as a roadmap for future researchers to work on the key areas of weaknesses highlighted by this research for achieving greater success in their research as well as for the construction industry.

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Appendices

Appendix-I: Sampler Questionnaire

Nottingham Trent University

Health and Safety Management

Page 1: Questionnaire Information

RESEARCH CONSENT INFORMATION SHEET

You are invited to take part in a research study because, you are a construction professional, and you are generally connected to Health and Safety management in the construction industry. Before you decide whether or not to take part, it is important for you to understand why the research is being done and what it will involve. Please take the time to read the following information carefully.

RESEARCH TITLE

Development of Immersive Safety Management Framework to Improve H&S Performance of Construction Projects

PURPOSE OF THIS RESEARCH

This project is being undertaken as a part of a PhD research at Nottingham Trent University. It is important for you to know that **this is an independent research and is Not attached to your organization.** The study investigates the current Health and Safety practices in the construction sector to find out the area of weakness and propose a novel framework for H&S management of the construction projects.

WHAT WILL HAPPEN IF I TAKE PART

1 / 19

If you decide to take part in the study, please select the button "I agree to participate". After that survey questions will appear which will be regarding Health and Safety practices in your organization. You are free to decline to answer any particular question you do not wish to answer. Your participation in this research is voluntary and should take approximately **10-12 minutes.**

CONFIDENTIALITY

Data collected from this experiment will be confidential and anonymous. No personal details will be collected about the participants and the tool used to send survey questions does not collect identifying information such as your name, email address, or IP address. Therefore, your responses will remain anonymous.

WHAT ARE MY RIGHTS AS RESEARCH PARTICIPANT?

- It is your right to decide whether or not to take part. Even if you have decided to take part you can still withdraw your data from this research with-in **One week** after submission and without giving any reasons. If you wish to withdraw your data after one week of your submission, it cannot be erased and may still be used in the project analysis. However, entire data will be destroyed when the research finishes in **January 2022**. If you wish to withdraw you need to contact a PhD student on the details provided below.
- You have the right to remain anonymous in any write-up (published or not) of the information generated during this interview.
- You have the right to refuse to answer any or all of the questions you will be asked.
- You also have the right to specify the terms and limits of use (i.e. full or partial) of the information generated during the interview.
- You have the opportunity to ask questions about this research and these should be answered to your satisfaction.

RESEARCH TEAM

Research Team	Research Role	Contact Details
Umair Khalid	Research Student	umair.khalid2017@my.ntu.ac.uk

Amritpal Sagoo	Director of Studies	amrit.sagoo@ntu.ac.uk
Benachir Medjdoub	Co-Supervisor	benachir.medjdoub@ntu.ac.uk

Page 2: Consent Form

CONSENT FORM

All participation in the research project is voluntary. If do you agree to be part of the project, we would like to use the information to develop a report, but your name and identity will remain anonymous and optional to write.

This project has been reviewed by and received ethics clearance through, the Nottingham Trent University Joint Inter College Ethics Committee.

Please read the following statements:

- I have had sufficient information to decide whether or not you wish to take part in the study.
- I understand that I am free to withdraw from the research at any time by informing the researcher of this decision.
- I understand that the information I give will be treated in the strictest confidence.
- I agree to take part in the study.
- I understand that quotations, which will be made anonymous, from this research may be included in the material published from this research.
- I am willing to participate in an interview as part of this research project.
- I understand that anonymized data may be used in other studies in line with the University Research Data Management Policy

Age: (This will be kept anonymous)

Job Role: (This will be kept anonymous)

Project Types Worked On: (This will be kept anonymous)

Safety Certification (If any): (This will be kept anonymous)

By clicking the "Next" button I agree to the above statements and would like to take part in the research.

Page 3: Section-I: Safety Management System

This part contains the list of multiple-choice questions seeking your answers on Safety Management System in your organisation. Please select the most appropriate answer in your knowledge.

	Yes	No	Not Sure
Does your organisation employ a safety management system in your organisation?	○	○	○
Does your organisation have a comprehensive safety management policy?	○	○	○
Does safety has given priority in the organisation's official plans and strategies.	○	○	○
Does the risk assessment carried out during health and safety planning?	○	○	○
Does the Health and Safety policy conveyed to all relevant stakeholders?	○	○	○
Does the safety policy in your organisation describe safety roles and responsibilities?	○	○	○
Does your organisation undertake health and safety induction training for all new employees?	○	○	○
Does your organisation offer job-specific training to the employees?	○	○	○
Does your company have an internal health and safety department?	○	○	○
Does your company undertake formal site health and safety inspections?	○	○	○

Page 4: Section-II: Accident Causation

This part contains the list of multiple-choice questions seeking your answers on accident causation.

Please select the most appropriate answer in your opinion.

Construction sites are considered as most vulnerable places, why do you accidents happen on construction sites?

- Lack of Safety Regulation/Guidelines
- Ineffective Safety Panning
- Inappropriate Risk Assessment
- All of the above
- Other

If you selected Other, please specify:

From the given options, which one do you think is the leading reason for the accidents?

- Equipment/Machinery
- Human Error
- Technology
- Complex sites
- Other

If you selected Other, please specify:

Considering the safety management factors, which Factor causes most of the accidents?

- Organisational Factors
- Regulatory Factors
- Human Factor
- Social Factors
- Other

If you selected Other, please specify:

What do you think, how accidents can be prevented?

- By efficient supervision
- By managing Human Factor
- By effective risk assessment
- Other

If you selected Other, please specify:

From the construction team, who do you think is responsible for accidents on construction sites?

- Top Management
- Safety Manager
- Workers on sites
- All of the above

In the organisation hierarchy, which organisational levels can be affected by 'Human Factor'?

- Operational Level
- Managerial Level
- Site-worker level
- All of the above

In your experience, how do you think Top management involves in the accidents at the workplace?

- Improper risk perception
- Lack of safety awareness
- Lack of safety Knowledge
- Other

If you selected Other, please specify:

In your experience, how does site workers initiate accidents?

- ○ Unsafe Actions
- ○ Lack of Training
- ○ Miscommunication
- ○ Workload
- ○ Other

If you selected Other, please specify:

____

In your opinion, why "Unsafe Actions" are carried out by the construction workers. (You can select multiple options)

- ☐ In-appropriate behaviour
- ☐ Unsafe Attitude
- ☐ Risk assessment ability
- ☐ Lack of Training
- ☐ Other

If you selected Other, please specify:

____

Page 5: Human Factor in Accident Causation

From the option below, what defines the "Human Factor" at the workplace. (you can select multiple options)

- ☐ Attitude
- ☐ Behaviour
- ☐ Commitment
- ☐ Risk Perception
- ☐ Safety Knowledge
- ☐ Experience
- ☐ Hazard Awareness
- ☐ Other

If you selected Other, please specify:

During which safety stage do you think "Human Factor" affect the most?

- ○ Planning
- ○ Implementation
- ○ Inspection
- ○ All of the above

Based on your understanding of Human Factor, how important do you think these attributes are regarding human factor. 0 - Not Important at all 5 -

Extremely Important

	0 - Not at all Important | 5 - Extremely Important					
	0	1	2	3	4	5
Behaviour	○	○	○	○	○	○
Commitment	○	○	○	○	○	○
Attitude	○	○	○	○	○	○
Education	○	○	○	○	○	○
Risk perception	○	○	○	○	○	○
Safety Awareness	○	○	○	○	○	○
Experience	○	○	○	○	○	○
Hazard awareness	○	○	○	○	○	○

Do you think the "human factor" should be assessed for critical tasks?

More info

- ☐ Yes
- ☐ No
- ☐ Not Sure

In the construction industry, which of the following Human Reliability assessment methods are you familiar with? (you can choose multiple options)

More info

- ☐ Human Factor Analysis & Classification System (HFACS)
- ☐ human error assessment and reduction technique (HEART)
- ☐ Cognitive Reliability and Error Analysis Method (CREAM)
- ☐ None of the above

- [ ] Other

If you selected Other, please specify:

How do you think Human Factors can be measured?

- ○ Measuring Personal Traits
- ○ Specialist Judgement
- ○ Risk Assessment
- ○ Method Statement
- ○ None of the above

In your opinion, which would be the preferable way of Human Factor assessment from the options below?

- ○ Questionnaire to seek employee response explaining different scenario's
- ○ Using Immersive technology, monitor the employee in real-time situation
- ○ Verbal Discussion of safety details
- ○ None of the above

Immersive technology can imitate the real situations, do you think it can be helpful for 'human factor' and behavioural assessment towards safety?

- ○ Yes, it can be helpful

- No, the existing methods are better
- Not Sure

Do you think 'human factor' can be improved through training using immersive technology by imitating real-time scenario's?

- Yes, it can be of improved enormously
- Not Sure
- No, the existing methods are better

'Human Factor' is a measure of Attitude, commitment, risk perception, hazard recognition & competence. Do you think these traits can be measured by creating a real-time construction environment using immersive technology?

- Yes, these can be measured by monitoring employee response under different scenario's
- Not Sure
- No, these can't be measured using immersive technology

If you are given an option to fill a questionnaire or perform a task in the immersive environment (VR). which one would you prefer?

- Immersive technology (VR)
- Questionnaire
- Not Sure
- None of the above

Page 6: Section-III: Human Factor Measurement

This part contains the list of multiple-choice questions seeking your answers on Human Factor Measurement.

Please select the most appropriate answer in your opinion.

In the construction environment, what do you think is a measure of "human-behaviour" towards H&S?

- Employees Actions
- Working Style
- Speed of Work
- None of the above

Which one from the given options describes the attributes of 'attitude' at work?

- Honesty, commitment, consistency, diligence
- Hard work, time, working method
- communication, work speed, Intelligence
- None of the above

Using the worker's actions, how would you assess the worker's attitude towards health and safety at the construction site?

- Commitment to safety indicators
- Follow safety instructions
- Attention to safety risks

- All of the above

In the construction environment, what will be the measure of 'commitment' towards health and safety at the workplace?

- Attention to safety details
- Follow safety instructions
- Communication of safety details
- All of the above

Lack of safety awareness on the construction site can;

- be helpful to achieve the goals
- Lead towards the accident
- speed-up the construction progress
- None of the above

In the construction environment, how can we measure the "safety awareness" of a construction worker?

- Observing his actions
- By considering his experience
- Using his confidence
- By a verbal discussion

By considering the worker's actions, what would be the measure of 'hazard awareness' on construction environment?

- Competence
- Recognition of safety hazards
- Hard-work
- Commitment
- Other

If you selected Other, please specify:

In the construction environment, what will be the measure the of 'Competence' of a construction work towards safety?

- Well-recognition of hazards
- Good risk perception
- Safety Knowledge
- All of the above
- Other

If you selected Other, please specify:

In the construction environment, what would be the most effective measure of 'risk perception'?

- Carefulness towards risks

- ○ Recognition of most of the risks
- ○ Work according to method statement
- ○ Communication
- ○ Other

If you selected Other, please specify:

Page 7: Final page

Thank you for taking part in the questionnaire.

Appendix-II: Semi-Structure Interview Sampler

PARTICIPANT INFORMATION SHEET

You are invited to take part in a research study because, you are a construction professional, and you are generally connected to Health and Safety management in the construction industry. Before you decide whether or not to take part, it is important for you to understand why the research is being done and what it will involve. Please take the time to read the following information carefully.

RESEARCH TITLE

Investigation into the development of a Human Reliability Analysis Framework for the Safety Management of Construction Projects

PURPOSE OF THIS RESEARCH

This project is being undertaken as a part of a PhD research at Nottingham Trent University. It is important for you to know that this is an independent research and is Not attached to your organization. The study investigates the impact of the human factor on health and safety management and develops an immersive human reliability assessment framework to improve health and safety performance.

WHAT WILL HAPPEN IF I TAKE PART

If you decide to take part in the study, please select the button "I agree to participate". After that survey questions will appear which will be regarding Health and Safety practices in your organization. You are free to decline to answer any particular question you do not wish to answer. Your participation in this research is voluntary and should take approximately 10-12 minutes.

CONFIDENTIALITY

Data collected from this experiment will be confidential and anonymous. No personal details will be collected about the participants and the tool used to send survey questions does not collect identifying information such as your name, email address, or IP address. Therefore, your responses will remain anonymous.

WHAT ARE MY RIGHTS AS RESEARCH PARTICIPANT?

- It is your right to decide whether or not to take part. Even if you have decided to take part you can still withdraw your data from this research with-in One week after submission and without giving any reasons. If you wish to withdraw your data after one week of your submission, it cannot be erased and may still be used in the project analysis. However, entire data will be destroyed when the research finishes in January

2022. If you wish to withdraw you need to contact a PhD student on the details provided below.

- You have the right to remain anonymous in any write-up (published or not) of the information generated during this interview.
- You have the right to refuse to answer any or all of the questions you will be asked.
- You also have the right to specify the terms and limits of use (i.e. full or partial) of the information generated during the interview.
- You have the opportunity to ask questions about this research and these should be answered to your satisfaction.

RESEARCH TEAM

Research Team	Research Role	Contact Details
Umair Khalid	Research Student	umair.khalid2017@my.ntu.ac.uk
Amritpal Sagoo	Director of Studies	amrit.sagoo@ntu.ac.uk
Benachir Medjdoub	Co-Supervisor	benachir.medjdoub@ntu.ac.uk

Participant Signature:

____

CONSENT FORM

All participation in the research project is voluntary. If do you agree to be part of the project, we would like to use the information to develop a report, but your name and identity will remain anonymous and optional to write.

This project has been reviewed by and received ethics clearance through, the Nottingham Trent University Joint Inter College Ethics Committee.

Please read the following statements:

- I have had sufficient information to decide whether or not you wish to take part in the study.
- I understand that I am free to withdraw from the research at any time by informing the researcher of this decision.
- I understand that the information I give will be treated in the strictest confidence.
- I agree to take part in the study.
- I understand that quotations, which will be made anonymous, from this research may be included in the material published from this research.
- I am willing to participate in an interview as part of this research project.
- I understand that anonymized data may be used in other studies in line with the University Research Data Management Policy.

Participant Name: ____

Participant Role: ____

Participant Signature: ____

Research Title: Investigation into the development of a Human Reliability Analysis Framework for the Safety Management of Construction Projects

Research Aims: The research aims to propose a framework to assess and mitigate the catastrophic effects of Human Errors in construction projects

Research Validation Questions

1. How safety is managed in your organization?
2. Do you have a safety management system in your organization?
   - What are the main components of a safety management system?
3. In your opinion, what is the main cause of accidents on construction sites?
   - Do you have a system in place to manage that cause of accidents?
4. In your career in construction, have you ever encountered an accident situation?
   - What was your organization's response to the accident?
   - Did your organization carry out an accident investigation?
   - If yes, what was the main reason behind the accident?
5. The research says human error/failure is the main reason behind accidents on construction sites. Do you agree with this statement?
   - If yes, How do you think human error leads to accidents?
   - If no, next question.

Framework Validation Questions

6. Do you have a system to mitigate human error during the planning phase of construction?
   - If yes, how does that system works? (If no, Question-7)
   - Is that system integrated with your safety management system?

7. Are you familiar with human reliability assessment (HRA) methods used in different industries?
    - If yes, What is your understanding of it and do you have a system in place for HRA? (If no, question-8)
    - How's your HRA system work? What are the essential parts of it?
    - Does it consider assessing error producing conditions, personal influencing factors (PIFs) and unsafe acts?

8. Human reliability assessment (HRA) involves the use of qualitative or quantitative methods to assess the human contribution to accidents. Many HRA methods are being used in manufacturing, chemical and other safety-critical industries. The basic principle of most of the HRA methods is based on identifying unsafety conditions and human error probability checks considering personal influencing factors (PIFs). PIFs include personal behaviour, attitude, commitment to work, risk perception, hazard analysis etc. Therefore it involves identifying the unsafe conditions and unsafe acts. Considering this;
    - Do you think unsafety conditions can be identified using 4D Modelling of the construction site during project planning?
    - If yes, next question
    - If no, what do you think is the best way of identifying the risk/unsafe condition at the preconstruction stage?

9. Considering the construction site simulations and taking into account the PIFs, do you think we can assess human error probability with the help of immersive technologies?
    - If yes, next question.
    - If no, in your experience, what would be the better way of human error assessment?

10. Would you agree that human error probabilities can be reduced by immersive training and unsafe conditions can be avoided by better planning?

11. This is the framework we have developed, what's your opinion on it?

Appendix-III: Initial Framework Publication

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ELSEVIER

Safety Management System (SMS) framework development – Mitigating the critical safety factors affecting Health and Safety performance in construction projects

Umair Khalid[a,*], Amrit Sagoo[b], Medjdoub Benachir[c]

[a] Nottingham Trent University, 74 Foxhall Road, Nottingham NG76LJ, United Kingdom
[b] Construction Management NTU, Maudslay 302, 50 Shakespeare St, Nottingham NG1 4FQ, United Kingdom
[c] School of Architecture Design and Built Environment, Maudslay 255, 50 Shakespeare St, Nottingham NG1 4FQ, United Kingdom

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Safety performance

ABSTRACT

The construction industry is known both for its significance in economic growth and its hazardous nature. The accidents on construction sites not only cause fatalities but also affect project performance severely in term of delayed completion, cost overruns, reduced quality and eventually low productivity. Statistically, poor safety performance is the main cause of the accident on sites due to the number of influencing factors. To improve safety performance, it is inevitable to investigate potential factors involved in safety management. This is a working paper and examines the relative importance of key factors influencing Health and Safety (H&S) performance and the rationale for developing a robust safety management system (SMS) that migrates all factors into one framework. This paper adopts an empirical research methodology based on literature review and secondary data gathered systematically from peer-reviewed journals. There are around sixty H&S factors and these have been assigned to cluster leadings forming six groups namely: 'organisational', 'managerial', 'legislative', 'social', 'environmental' and 'personnel' factors. In developing the rationale for the safety management system (SMS) framework it has become apparent that the effective safety performance can only be achieved through effective (1) implementation of safety regulations, (2) leadership, (3) safety planning, (4) safety compliance, (5) performance measurement, (6) risk assessment, (7) safety inspection, and (8) Safety Culture. These factors are interrelated with each other and they cannot be isolated, however, in order to significantly improve the safety performance target on construction projects, there is a need to re-alignment and re-balance the priorities assigned to factors influencing safety performance.

1. Introduction

The significance of the construction industry cannot be underestimated as it is considered one of the largest industries and most dynamic driver of the economy that employs millions of people in the country (Rostami et al., 2015). Around 2.4 million people in the UK work in the construction industry which contributes £113 billion to the country's economy equivalent to 6.8% of the country's GDP (Office of National Statistics, 2018). Despite its worth in generating revenue, it is also a well-known fact that the construction industry is one of the most hazardous, labour intensive, fragmented and dynamic industries (Wang et al., 2019) and ranked as the second top industry after agriculture with the highest accidents in 2018/2019 in the UK (HSC, 2019). In the United Kingdom, around 22% of total occupational fatalities are from the construction sector, as reported by the Health and Safety (H&S) Executive (HSE) (HSC, 2019). In 2018/19, 30 workers in the construction industry became the victim of fatal injuries, and 2420 faced non-fatal injuries at the workplace in Great Britain (HSC, 2019).

Latham report (1994) "Constructing the team" stated that no construction project is risk-free. Managing the H&S factors are therefore inevitable for the success of any construction project (Shi et al., 2018). A wealth of research has been carried out in the construction industry to identify the factors responsible for poor H&S management. However, most of the researchers have worked on the specific domain, projects or countries for analysis of H&S factors. For instance, Ismail et al. (2012) evaluated the behavioural factors regarding H&S management in

* Corresponding author. Telephone.: +44 7719 136419.
E-mail addresses: umair.qureshi107@gmail.com (U. Khalid), amrit.sagoo@ntu.ac.uk (A. Sagoo), benachir.medjdoub@ntu.ac.uk (M. Benachir).

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construction sites. Williams et al. (2019) investigated the factors influencing safety culture maturity in the construction industry. Hamid et al., (2019) found the causes of accidents in the Malaysian construction industry by analysing previous accidents on sites. Similarly, Gao et al. (2018) researched the factors organisations face in implementing safety practices in the construction industry. Choudhry (2017) penned on the factors affecting the productivity of construction projects. Similarly, some researchers have explored the factors affecting H&S management but focused on a specific country or region (Abdul-Rashid et al., 2007; Kadiri et al., 2014; Hamid et al., 2019).

This research undertakes an inclusive and systematic approach of reviewing H&S factors involved at all stages of a construction project and develop a SMS framework. Traditionally, the safety information used for safety planning does not cover all safety factors involved in development which are essential for the success of any SMS. However, this research, therefore, aims to first explore all safety factors involve in a typical construction project from planning till completion and develop a SMS framework to mitigate all the factors for success as well as improved safety performance. Hence, the research objectives include; (1) Explore the key factors affecting H&S management practices in a construction project through a systematic and comprehensive literature review of the past 15 years of research. (2) Analyse and classify the factors under different clusters using empirical analysis techniques. (3) Develop a SMS framework to manage and mitigate all the risks associated with H&S factors.

The rest of the article is structured as follow; section two highlight the state of the art literature on construction industry productivity and safety management in the construction industry. The literature review clarifies that the abundance, as well as the diversity in the research on the safety factors, emphasize the need for a systematic and comprehensive approach to explore the literature and highlight every possible safety factor mentioned by the researchers. Therefore, section three of this article presents the research methodology of data collection and analysis. Section four presents the empirical analysis of the collected data to classify safety factors into clusters for the development of SMS framework development which has been elaborated in section five. A comprehensive discussion has been made in section six on the SMS Framework followed by the conclusion in the last section.

2. Literature review

2.1. Construction safety and productivity

The uniqueness of construction is its hazardous nature and complexity due to a range of construction activities comprised of working on difficult situations and rely intensively on heavy machinery and equipment (Durdyev et al., 2017). Construction workers are exposed to hazardous working conditions such as working at heights, stuck and caught by construction equipment and machinery on sites that often lead to accidents (Mohammadi et al., 2018). The notorious nature of the construction industry has, therefore, catastrophic effects on productivity which is traditionally measured in the parameters of cost, quality and time (Hare et al., 2006). Alkaissy et al. (2019) analysed safety data for the past two decades and mentioned that failure to model H&S risks lead to incidents eventually lower productivity. Moreover, Abubakar Muhammad et al. (2015) stated that among the other performance parameters, H&S is considered as one of the key parameters besides the traditional parameters (time, quality and cost) which can easily be compromised by the lack of effective H&S management. Thus, the improvement in occupational health and safety stands inevitable as well as a great concern for the researchers as the accidents come with enormous cost and undermined productivity.

Asides from economic loss, this issue also comes with the loss of indispensable human lives, illness, skilled workers and huge compensation costs (Benjaoran and Bhokha, 2010). Furthermore, the accident costs could be categorised into direct and indirect costs in the construction industry (Haupt and Pillay, 2016). The direct costs are termed as 'tip of the iceberg' involve the accident insurance compensation costs and injuries cost. The UK economy lost £1.2 billion in regards to the direct costs due to the work-related illnesses and accidents in the construction sites that comprises 8% of total cost across all industries (HSC, 2019). Subsequently, Smallwood and Haupt (2007) stated that indirect or submerged costs are 14.2 times direct costs triggers in term of reduced performance, low productivity, delays and loss of property.

2.2. Construction safety management

Considering the hazardous nature of the construction industry several countries have regulated the safety management systems (SMS). The United Kingdom's Health and Safety Commission (HSC) legislated Health and Safety at work etc Act 1974 to propose the occupational health and safety guidelines. Health and safety at work etc Act 1974 also imply duties on all the stakeholders to ensure the safety of their workers including members of the public during the project. Subsequently, the principal set of regulations for construction was introduced in 2007 called Construction (Design and Management) Regulations 2007 (CDM). CDM regulations imply roles and responsibilities on all parties to contribute to the health and safety of construction projects. Detailed requirements for those involved in pre-construction and planning phases are explicitly mentioned in CDM Regulations. Moreover, the CDM regulations are meant to bring together all the stakeholders involved in the design and construction process by creating the safety culture in the industry to overcome the health and safety issues that ascend at different stages of development (Zhou et al., 2012).

Safety management had been an area of great concern for researchers in the past decade. Jin et al. (2018) revealed that the safety management program had been an area of interest for researchers in the past decade after reviewing 513 articles in the construction safety domain. Construction safety management is the process of managing safety regulations, practices and procedures on a construction site (Abas et al., 2020). Besides safety regulations, safety management practices also contribute momentously to safety management. The literature reveals that the traditional H&S practice is carried out in two phases, during the first phase called as pre-construction phase, safety is planned and executed and monitored in construction phase of construction (Zhang et al., 2013). However, many researchers also stated that the current safety practices rely immensely on human's perception towards safety, knowledge, experience and cognitive abilities to identify hazardous situation (Hongling et al., 2016; Wang et al., 2016; Nawaz et al., 2020). Carter and Smith (2006) argued that the hazard identification by worker's cognitive abilities deemed impossible due to the dynamic, unpredictable nature and uniqueness of construction sites. Failure to identify safety hazards is the primary cause of accidents in the construction industry (Guo et al., 2017). Therefore, it is essential to explore every potential safety factors that could cause an accident or an injury on the construction site.

Various researchers in the construction industry have studied safety management performance and explored unprecedented factors influencing H&S management. For instance, Hare et al. (2006) stated that effective safety planning is one of the utmost important factors that can play a vital role in the success of any construction project. Azhar (2017) believes that H&S planning is still carried out separately from project planning and lack of integration could lead to the accident during the construction phase. As when the hazard identification is not entirely assessed with project planning, workers are more venerable and exposed to unexpected hazards and can suffer catastrophic damage (Albert et al., 2014). Integrated H&S planning is therefore recognised as one of the factors that could be death with effectively.

One of the critical parts of safety management is hazard identification and the ability to identify the potential hazards on construction sites before initiating the actual work is a decisive factor to mitigate the risks

(Eiris et al., 2018). Similarly, workers training, safety culture, safety behaviour, risk assessment, stakeholders relationship, resource allocation for safety, and the complexity of the construction projects are some of the renowned factors contributing to poor safety management highlighted by the researchers (Zou et al., 2007; Ismail et al., 2012; Agumba and Haupt, 2014; Jafari et al., 2014; Xia et al., 2018; Wang et al., 2019). There has been ample research on safety factors by researchers all around the world either specific to their countries or projects, however, no holistic has been adopted to figure out all possible safety factors in the construction industry. This research, therefore, entails a systematic approach to rigorously review state-of-the-art literature on factors affecting safety management and establish a SMS by mitigating all safety factors involved.

3. Research methodology

In the academic world, developing research-based on existing knowledge is the root of all research activities (Snyder, 2019). It is usually considered as the literature review plays a supportive role in most of the cases, however, it can also be an independent study. A literature review research establishes the research theory by integrating the findings and perspectives of previously done empirical (Okoli and Schabram, 2010). A comprehensive and effective literature review develops a building block for evolving the research findings and theory development (Webster and Watson, 2002). Through the integration of the findings and outcomes of the previous studies, the literature review can address the research questions precisely and in a more effective way (Snyder, 2019).

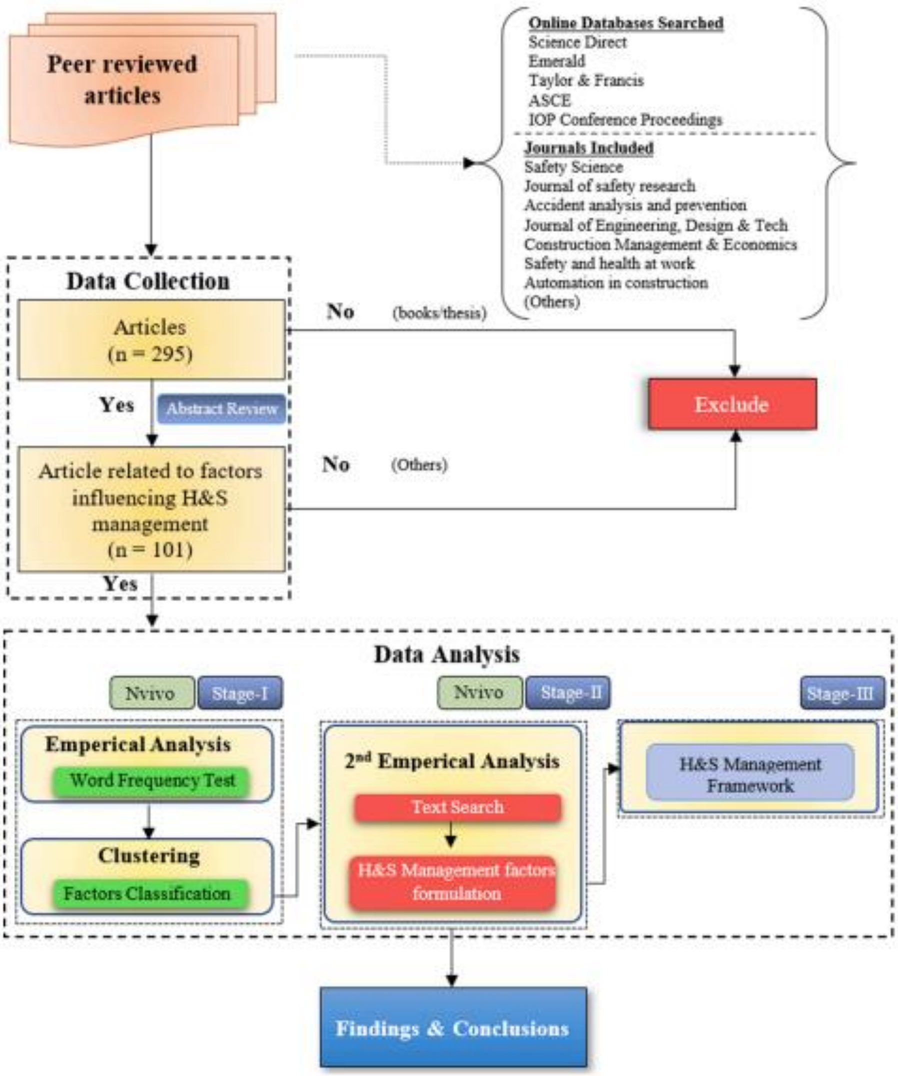

Fig. 1. Research methodology.

3.1. Data collection

The study entails the systematic literature review as a research methodology to explore the factors causing H&S management issues in the construction industry among the peer-reviewed articles and develop a SMS framework mitigating all factors. The review was performed by selecting the articles from the notable journals and conference proceedings that have been used extensively by the researchers and practitioners in the area based on the specific search criterion. The research methodology used has been shown in the Fig. 1.

The first step in the review process involved the selection of the articles, we selected 295 articles from the peer-reviewed databases namely; Science Direct, Emerald, ASCE, Taylors & Francis and a few IOP conference proceedings publications. The selection criterion designed on the specific search strings related to research objectives and time of publication. The search strings used were; (1) Health and safety factors in construction, (2) Factors influencing/affecting H&S Management in construction, (3) Accident causal factors in construction, (4) Factors influencing safety performance, and (5) Factors causing poor Occupational health and safety (OHS) management. Secondly, no article selected older than 2005 as research aimed to review the past 15 year's articles to get insight into the latest safety factors. Therefore, during the review process, the articles were selected based on the title, year of publication and keywords.

3.2. Literature selection

An extensive search has been conducted to locate the publications related to the factors in H&S management. The downloaded literature passed the screening process to outline the most appropriate articles related to the research objectives. For that purpose, the abstract was reviewed for all 295 articles and a total of 106 articles specific to H&S management factors were selected for the empirical analysis. The articles were then classified by the year of publication and type of publication.

Out of the selected articles, 54% of them ranged between the past five years as shown in Fig. 2. Moreover, for the review analysis, only journal and conference papers were selected, and no books or thesis were included for the research to evaluate the most adequate peer-reviewed knowledge. Subsequently, 86% of the chosen articles were journals publications and 14% were conference proceedings as indicated in Fig. 3. The sources of the journal articles and conference proceedings are listed in Table 1.

4. Data analysis

After the selection of pertinent state-of-the-art literature from peer-reviewed journals, the analysis was done in three stages. In the first stage, the empirical analysis has been performed with NVivo 12 Pro using the word frequency function on the selected articles to conceptualize the safety factors taxonomy. The minimum letter length was set to "Four (4) Letters" and grouping criteria was set to 'Exact Match' for word frequency test to get the most appropriate blend of words called 'safety concepts' from the literature. Table 2 and Fig. 4 show the result of the word frequency test identifying all the safety concepts related to H&S management.

Subsequently, the clustering has been performed after contextualizing the safety concepts (Table 2) generated by the word frequency test to categorize them into numerous groups. The clustering performed was based on the comparative study of the context of the words generated by the empirical study. The analysis indicated that these concepts can be interpreted into six different clusters namely 'organisational', 'managerial', 'legislative', 'social', 'environmental' and 'personnel'. It has also been indicated that most of these concepts can be interpreted in multiple groups. For instance, the word like 'management', can be linked to the 'organisational', 'managerial', 'legislative', 'environmental' and 'personnel' groups. Fig. 5 shows the cluster analysis of the complete list of safety concepts based on their safety context.

Furthermore, the cluster analysis also indicated that many of the concepts were interlinked and phrased as H&S management factor when combined. For instance, the word 'hazard' and 'perception' together exhibit adequate H&S management factor cited by many researchers (Khosravi et al., 2014; Wang et al., 2016; Durdyev et al., 2017; Gunduz and Laitinen, 2017; Gul, 2018; Machfudiyanto et al., 2019; Othman et al., 2020). Therefore, in the second stage, another empirical analysis was performed to formulate the H&S management factors associated with the safety concepts generated in stage one. Each of the safety concepts was analysed separately with NVivo 12Pro Text Search

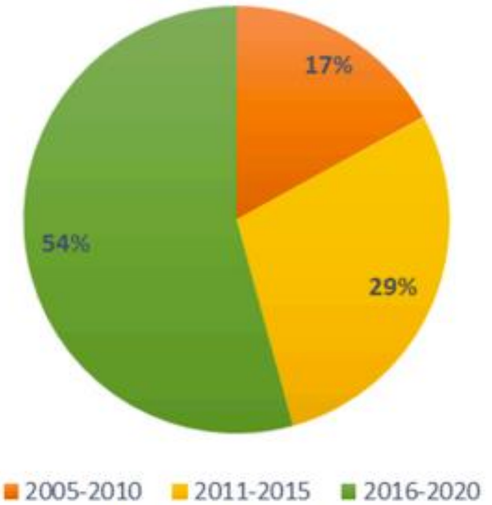

Fig. 2. Literature Classification by year of Publication.

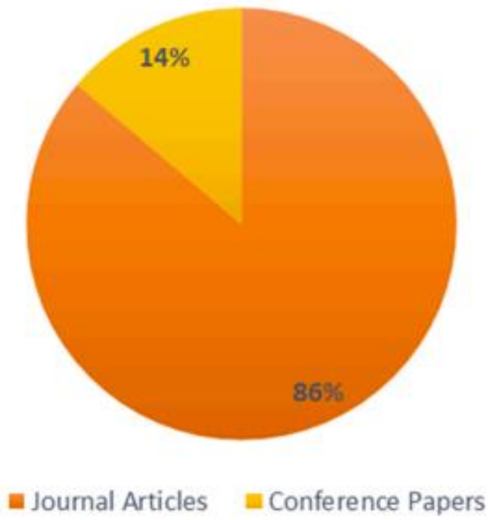

Fig. 3. Literature Classification by type of Article.

Table 1
List of Journals.

Journals	No# of Papers
Safety Science	17
International Journal of Occupational Safety and Ergonomics	8
Construction Management and Economics	5
Engineering	5
IOP Conference Series: Earth and Environmental Science	5
Journal of Engineering	5
IOP Conference Series: Materials Science and Engineering	4
Journal of Construction Engineering and Management	4
Journal of Safety Research	4
International Journal of Project Management	3
Procedia - Social and Behavioural Sciences	3
Accident Analysis and Prevention	3
Association of Researchers in Construction Management	2
Automation in Construction	2
Journal of Management in Engineering	2
5th International Project and Construction Management Conference (IPCMC 2018)	1
Advances in Civil Engineering	1
American Journal of Engineering Research	1
Applied Ergonomics	1
Australasian Journal of Construction Economics and Building	1
Automation in Construction	1
Benchmarking	1
Built Environment Project and Asset Management	1
Construction Economics and Building	1
Construction Innovation	1
Data in Brief	1
Human and Ecological Risk Assessment	1
IFAC-Papers Online	1
International Journal of Environmental Research and Public Health	1
International Journal of Industrial Ergonomics	1
International Journal of Managing Projects in Business	1
International Journal of Occupational Hygiene	1
International Journal of Productivity and Performance Management	1
International Review of Management and Marketing	1
IOP Conference Series: Earth and Environmental Science PAPER	1
IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE)	1
Journal of Building Engineering	1
Journal of Civil Engineering and Management	1
Journal of Construction in Developing Countries	1
Journal of Physics: Conference Series	1
MANAS Journal of Engineering	1
Policy and Practice in Health and Safety	1
Procedia Computer Science	1
Procedia Engineering	1
Safety and Health at Work	1
Safety officers and workers were asked to indicate how effective	1
Total Quality Management and Business Excellence	1
World Journal of Science	1
Journal of Financial Management of Property and Construction	1

function using the selected literature and a list of sixty-three H&S management factors was compiled in six different clusters. Moreover, as aforesaid the analysis revealed that several factors are linked with multiple clusters and can only be mitigated if managed in all related clusters, for instance, safety perception is a part of organisations, managerial and personnel clusters. Therefore, some of the safety factors will be listed in multiple clusters in the safety factors table. Table 3 shows the list of all contributory H&S management factor found in the literature.

Fig. 6 illustrates six H&S management clusters developed in stage-2 of the research.

5. Safety management system framework

A safety management system (SMS) framework is defined by HSE and international standards as a systematic and proactive approach to managing safety policies and procedures to mitigate the risks involved in the project. After the formulation and clustering of H&S factors, the third and final phase of research intended to propose an SMS framework

Table 2
Safety concepts count and weight (%).

Words	Count	Weighted Percentage (%)
management	4764	1.22
risk	2558	0.65
workers	2333	0.60
site	1439	0.37
data	1389	0.35
training	1369	0.35
climate	1245	0.32
design	1052	0.27
culture	854	0.22
assessment	811	0.21
contractors	781	0.20
practices	742	0.19
environment	708	0.18
quality	704	0.18
time	696	0.18
equipment	691	0.18
information	671	0.17
cost	659	0.17
experience	625	0.16
unsafe	612	0.16
behaviour	599	0.15
method	587	0.15
planning	567	0.14
implementation	548	0.14
knowledge	545	0.14
productivity	508	0.13
workplace	500	0.13
approach	479	0.12
hazards	474	0.12
relationship	448	0.11
human	440	0.11
commitment	432	0.11
measures	431	0.11
technology	428	0.11
communication	422	0.11
systems	420	0.11
education	415	0.11
activities	404	0.10
regulations	404	0.10
organization	396	0.10
compliance	395	0.10
tools	371	0.09
perception	354	0.09
indicators	353	0.09
procedures	353	0.09
resources	338	0.09
policy	325	0.08
supervisors	321	0.08
materials	318	0.08
awareness	307	0.08
decision	307	0.08
attitude	299	0.08
social	297	0.08
understanding	285	0.07
involvement	283	0.07
motivation	266	0.07
stakeholders	266	0.07
technologies	265	0.07
plan	262	0.07
responsibility	259	0.07
audit	258	0.07

aligned with all the associated H&S management clusters found in stage-2 of the empirical analysis. The proposed framework showcases the relationship between safety factors and safety drivers to better understand and manage the safety factors which if unattended lead to the incidents on site. The adequate implementation of the SMS framework improves the safety performance taking into account the safety factors and eventually leads to the success of the project. In this phase, the proposed SMS framework was developed in three tiers to develop a methodical approach to mitigate and manage all H&S factors. The tier-one routes all the safety factors through two drivers; 'Safety

Fig. 4. Safety Concepts.

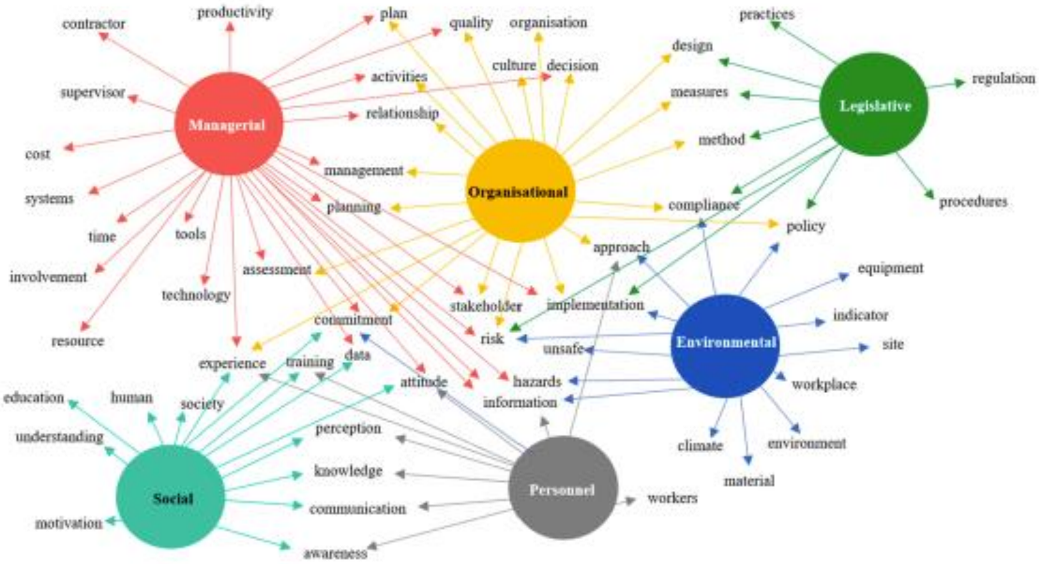

Fig. 5. Cluster Analysis of safety Concepts.

Administration' and 'Information Technology (IT) Adoption' listed in Table 4.

H&S literature explicitly illustrates the use of two drivers as safety management and risk mitigation techniques. These drivers were formed based on the thorough literature review which on one side states that managing safety policies and procedures defines SMS framework, however, a wealth of literature also argues intensely on the adoption of information technologies for safety performance promotion and risk assessment for improved safety performance. For instance, Table 5 show the number of researcher's work endorsing 'Safety Administration' and

Table 3
H&S management Factors.

Organisational		
F1 F2 F3 F4 F5 F6 F7 F8 F9 F10 F11 F12 F13 F14 F15	Safety Management Policy design Safety audit Safety culture Commitment Approach Safety Perception Implementation plan Safety compliance Information management Structure & responsibilities Stakeholders management Resource management Quality Economics	(Haslam et al., 2005; Hallowell, 2012; Zhou et al., 2015; Aksorn and Hadikusumo, 2008; Wang et al., 2016; Li et al., 2018; Ismail et al., 2012; Gao et al., 2018; Durdyev et al., 2017; Jaafar et al., 2018; Gunduz and Ahsan, 2018; Pereira et al., 2020)
Managerial		
F16 F17 F18 F19 F20 F21 F22 F23 F24 F25 F26 F27 F28 F29 F30 F31 F32 F33 F34 F35 F36 F37	Safety planning Safety management system Training Safety cost design Safety compliance Decision making Communication Knowledge sharing Safety Education Commitment to safety Safety attitude Safety culture Safety perception Contractor experience Supervision & monitoring Enforcement Safety Tools/ technology Safety meetings Risk Assessment Hazard identification Data Sharing Safety investment/ incentives	(Othman et al., 2020; Khosravi et al., 2014; Aksorn and Hadikusumo, 2008; Haslam et al., 2005; Wang et al., 2016; Al Haadir and Panuwatwanich, 2011; Gunduz and Ahsan, 2018; Wang et al., 2016; Aksorn and Hadikusumo, 2007; Park and Kim, 2013; Pereira et al., 2020; Jaafar et al., 2018; Gul, 2018; Gao et al., 2018; Durdyev et al., 2017; Zahoor et al., 2017; Nawaz et al., 2020; Mohammadi et al., 2018; Abas et al., 2020; Al Haadir and Panuwatwanich, 2011; Ismail et al., 2012; Durdyev et al., 2017; Mathar et al., 2020; Mollo et al., 2019; Zhou et al., 2015; Li et al., 2018; Hallowell, 2012; Gunduz and Ahsan, 2018)
Legislative		
F38 F39 F40 F41 F42 F43	Safety code Compliance Safety policy Safety methods Commitment to regulation Enforcement plan	(Zhou et al., 2015; Wang et al., 2016; Aksorn and Hadikusumo, 2008; Li et al., 2018; Durdyev et al., 2017; Hallowell, 2012; Gao et al., 2018; Pereira et al., 2020; Ismail et al., 2012)
Social		
F44 F45 F46 F47 F48	Society culture Workers ethnicity Education & commitment Safety perception Awareness & motivation	(Zhou et al., 2015; Wang et al., 2016; Li et al., 2018; Aksorn and Hadikusumo, 2008; Li et al., 2018; Pereira et al., 2020; Durdyev et al., 2017; Hallowell, 2012; Gao et al., 2018; Gunduz and Ahsan, 2018; Ismail et al., 2012)
Environmental		
F49 F50 F51 F52 F53 F54 F55 F56	Construction site Unsafe climate Safety hazards Safety indicators Unseen risks Equipment & materials Uncontrolled conditions Weather	(Zhou et al., 2015; Hu et al., 2011; Li et al., 2018; Hallowell, 2012; Gao et al., 2018; Wang et al., 2016; Ismail et al., 2012; Durdyev et al., 2017; Pereira et al., 2020; Gunduz and Ahsan, 2018; Jaafar et al., 2018)
Personnel		
F57 F58 F59 F60 F61 F62 F63	Attitude Risk awareness Education Safety Perception Commitment to plan Hazard perception Training	(Wang et al., 2016; Zhou et al., 2015; Li et al., 2018; Hu et al., 2011; Gunduz and Ahsan, 2018; Pereira et al., 2020; Li et al., 2018; Li et al., 2018; Hallowell, 2012; Gao et al., 2018; Ismail et al., 2012; Durdyev et al., 2017)

Fig. 6. H&S Factor Clusters.

Table 4
Safety factors classification.

Safety Administration	IT Adoption
Program/Planning	Technology/tools/innovation
Legislation/policy/method	Communication/information/data-sharing
Competence/ knowledge	Planning/programming
Compliance/implementation	Training/education
Contractor/supervisor experience	Hazard identification/risk assessment
Leadership/commitment	Monitoring/supervision
Stakeholders/team management	Equipment/site mapping
Roles/responsibilities	Attitude/culture/perception/awareness
Resources/safety cost incentives/motivation	
Environment/equipment/materials	

different 'IT' technologies for a certain aspect of safety management. Fig. 7 shows the SMS framework developed in three tiers considering all the safety factors.

After defining the drivers of the SMS, tier-two comprises the four elements of safety management recommended by OSHA and ISO safety standards to include every aspect of safety management. The four elements derived were; 'safety policy', 'safety assurance', 'risk management', and 'safety promotion' which imitates the basic elements of safety management system i.e. planning, implementation, education

Table 5
Researchers endorsing safety administration & IT as safety drivers.

Safety Driver	Author
Safety Administration	(Machfudiyanto et al., 2019; Ismail et al., 2012; Choudhry, 2017; Wachter and Yorio, 2014; Fang et al., 2006; Zhou et al., 2008; Åsgård and Jørgensen, 2019; Chileshe and Dzisi, 2012; De Snoo et al., 2011; Li et al., 2018; Othman et al., 2020; Khosravi et al., 2014; Aksom and Hadikusumo, 2008; Haslam et al., 2005; Wang et al., 2016; Al Haadir and Panuwatwanich, 2011; Gunduz and Ahsan, 2018; Wang et al., 2016; Aksom and Hadikusumo, 2007; Pereira et al., 2020; Jaafar et al., 2018; Gul, 2018)
IT Adoption	(Benjaoran and Bhokha, 2010; Zhang et al., 2015; Choe and Leite, 2017; Frank Moore and Gheisari, 2019; Zhou and Ding, 2017; Bansal, 2011; Zhang et al., 2020; Park and Kim, 2013; Carter and Smith, 2006; de Melo et al. (2017); Ganah and John, 2017; Rwamamara et al., 2010; Balgheeth, 2016)

and inspection. The categorization of safety elements into two safety drivers demonstrates the safety management from the top level in the organization. Tier three further narrows down each safety element to safety components involved in the planning of that element for better understanding and control of safety. This tier indicates all the essential components entails in the accomplishment of an effective SMS framework. These essential components include: 'safety regulations', 'leadership', 'safety planning', 'safety compliance', 'performance measurement', 'hazard identification/risk assessment', 'safety inspection', 'safety culture'. Each of these components is discussed in detail and the relationship between safety components and safety factors is explained in section-6 of the article through literature and shown in Fig. 16. The discussion on each of the safety components highlights how safety factors are connected with safety components and validate the SMS framework from the literature review.

6. Results and discussion

6.1. *Safety policy*

The safety policy statement is the essential part of the SMS framework which states the organisation`s beliefs on fundamental regulations, commitment and responsibilities about health and safety management (Ismail et al., 2012). A successful safety policy not only leads to the success of safety objectives but also manifests the success of an organisation`s overall mission. Hence, the success of a safety policy depends on:

6.1.1. *Safety regulations*

The safety regulations are one of the decisive factors found in the research towards the successful implementation of health and safety. Many countries have implemented their H&S regulations such as the Occupational Safety and Health regulations in the United States, CDM 2015 British Standards Institute (Choudhry, 2017). Aforementioned, the CDM regulations 2007 development by the government commission was a big milestone in term of safety management. The safety regulations provide essential guidelines for safety management practices to accomplish positive safety results (Wachter and Yorio, 2014). Organisational values and culture have a direct impact on the successful implementation of safety regulations (Gao et al., 2018). Although safety management regulations play important role in managing safety, however, the extensive research on H&S factors revealed that successful application of the safety regulations can only be achieved by taking into account; organisational factors, safety compliance methods, and managerial factors (Gunduz and Ahsan, 2018). Fig. 8 below demonstrates each of the factors of safety regulations broken down into the contributing attributes of each factor.

6.1.2. *Leadership*

The consequentiality of safety culture has long been discussed in the safety literature and is perceived as the evolving safety values, perception and attitude of employees to improve the safety performance within the organisation (Fang et al, 2006). The leadership has the core commitment and responsibility towards developing a safety culture that leads towards a positive impact on the workers and improved safety performance (Umar, 2020). Moreover, the leadership has a direct role in defining safety policies, risk assessment, programme development, implementation plans, and evaluation (Li et al., 2018). The personal involvement of top leadership in safety planning and execution is recognized as the key component of safety management to achieve safety performance in the organisation (Machfudiyanto et al., 2019). The safety regulations and plans do not lead to success without competent leadership. Khdair (2011) also stated that leadership attitude is a decisive factor in achieving safety goals.

Nevertheless, the critical analysis of safety factors illustrates the

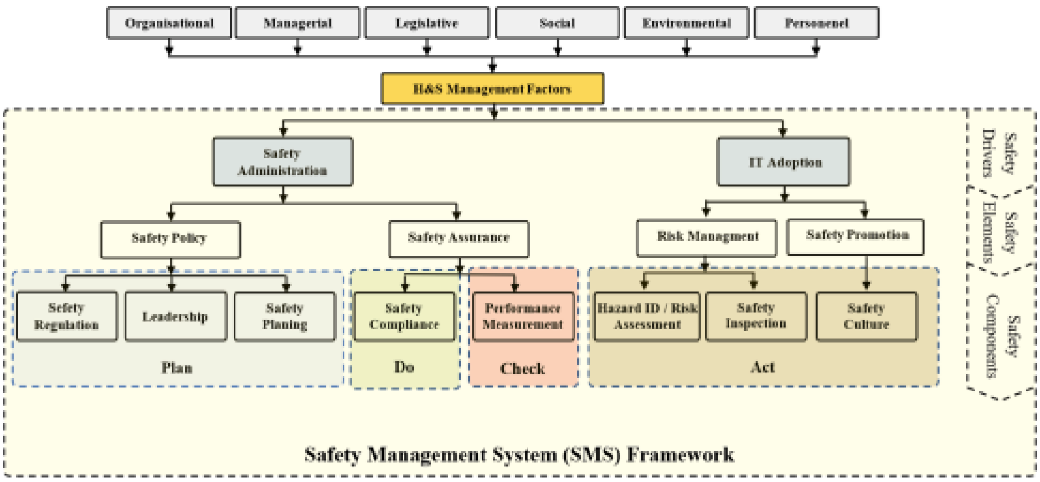

Fig. 7. Safety Management System (SMS) Framework.

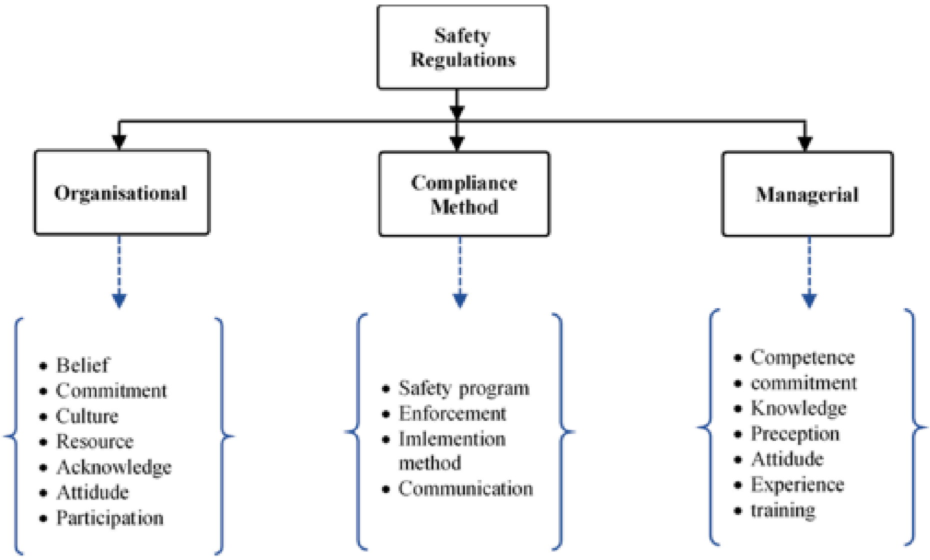

Fig. 8. Safety Regulation Factors.

significance of leadership and the related success attributes. Safety attitude and commitment are found as the key factors of effective leadership. Fig. 9 below demonstrates each of the factors of safety regulations broken down into the contributing traits of each factor.

6.1.3. Safety planning

Effective safety planning is recognized as one of the important factors that play a vital role in the success of any construction project (Hare, 2006). It is recognized as a two-stage process: planning and implementation (Zhang et al., 2013). The risk assessment and hazard identification are the essential parts of the safety planning that needs to be done at the pre-construction stage. The ability to identify the potential hazards on construction sites before initiating the actual work is a decisive part of the safety plan to mitigate the risks (Eiris et al., 2018). It doesn't only contribute to the prevention of accidents but also deters the ill health of the workers on construction sites (Bansal, 2011). Subsequently, safety planning also needs to consider at the earliest stages of project planning to mitigate the safety issues and relevant risks. The decisions made during the planning phase have an immense impact on the successful completion of the project (De Snoo et al., 2011).

One of the contributory factors of impaired safety performance is conducting safety planning separately from project planning and considered as the sole contractor's ressponsibility (Chantawit et al., 2005). Efforts have been made in the past to integrate safety planning

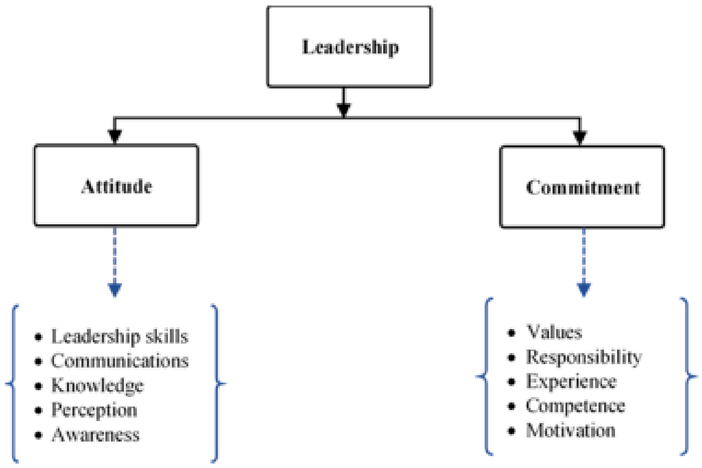

Fig. 9. Leadership Factors.

with project design, scheduling and cost planning to improve safety performance proactively. The construction CDM regulation (2007) in this regard provides the most integrated safety planning approach as well as involves every stakeholder in the safety planning process. It explicitly defines roles and responsibilities for everyone involved in the design and construction planning process at the pre-construction phase of the project (Zhou et al., 2012). The detailed analysis of safety factors highlighted safety planning as a substantial factor contributing to H&S management. Fig. 10 below demonstrates each of the factors of safety planning broken down into the contributing traits.

6.2. *Safety assurance*

Safety assurance is at the core of the safety management system that ensures the implementation of the systematic safety plan and continuous surveillance of safety performance throughout the development. In the construction industry, safety implementation starts with the application of safety regulations in the design and planning stages followed up by continuous inspection and monitoring during the construction phase of the task. The two aspects of safety implementation identified in the literature review are;

6.2.1. *Safety compliance*

Safety compliance in the construction industry is adhering to the safety procedures to carry out the work in the safest possible way (Zhou et al., 2008). The success of the safety management system depends momentously on the safety implementation plan. The research revealed that the good implementation of the safety management system enables the organisation to meet the safety as well as the overall project goals (Chileshe and Dzisi, 2012). In the United Kingdom, CDM regulations provide the key steps for the implementation of a safety management system that includes: (1) safety protective measures, (2) use of rights safety tools, (3) provide training and instructions (4) effective supervision (CDM, 2015). There is also a wealth of literature on safety implementation, the essential elements found in the literature are; proactive safety program, directions, education and training, clear roles and responsibilities and review method. A vital factor of a successful implementation program is to periodically educate and train the worker's to improve their knowledge as well as their safety awareness (Bavafa et al., 2017). Clear roles and responsibilities enable the management team to mitigate the potential risks and eventually accidents on construction sites (Yu et al., 2014). Fig. 11 below demonstrates each of the factors of safety implementation broken down into the contributing traits of each factor.

6.2.2. *Performance measurement*

The performance of any safety management system inevitably depends on continuous safety monitoring and review for the improvement of the system. It is recognised as an integral part of the safety management system that reflects success through continuous review and change management. Although the safety regulations enforced by the government around the globe set a self-regulatory approach to measuring safety performance, however, the construction professionals advocate for a personalised safety performance measurement framework. Williams et al. (2019) stated that hazard identification, monitoring and evaluation, and safety encouragement are the essential traits to be considered for the safety performance measurement. The analysis of extensive literature revealed the following as the factors of safety measurement; development of the supervisory team, monitoring of compliance, communication to the site workers, and participation in safety (Ng et al., 2005). The supervisory personnel qualification, experience, knowledge, safety awareness, training and commitment have a significant impact on performance measurement. Fig. 12 below shows the factors of performance measurement.

6.3. *Risk management*

Risk management is recognized as identifying and controlling the safety risks in the construction process to help the organisation meet the time, quality and financial goals (Serpella et al., 2014). The literature shows that this is one of the most important parts of the safety management system is risk identification and analysis. The decision made on the identified risks has an immense impact on the project overall performance. The risks are managed in two stages; at the pre-construction stage risks are identified and controlled during the design and planning phases, secondly, during the construction stage, site inspections are carried out to mitigate potential risks. Therefore, two characteristics of risk management are;

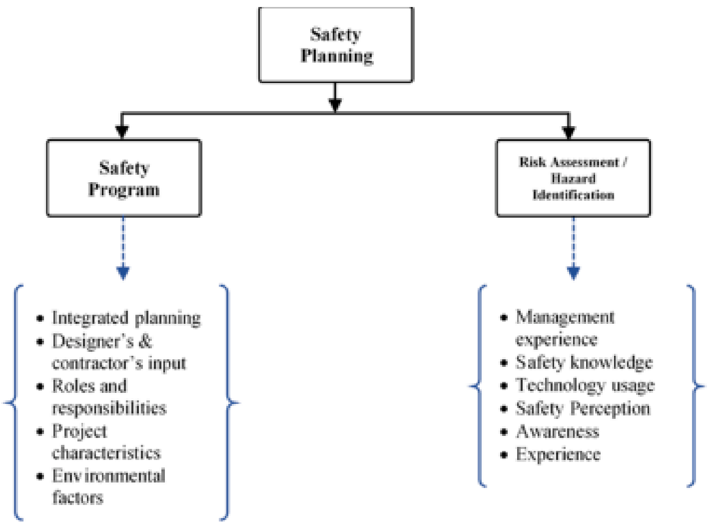

Fig. 10. Safety Planning Factors.

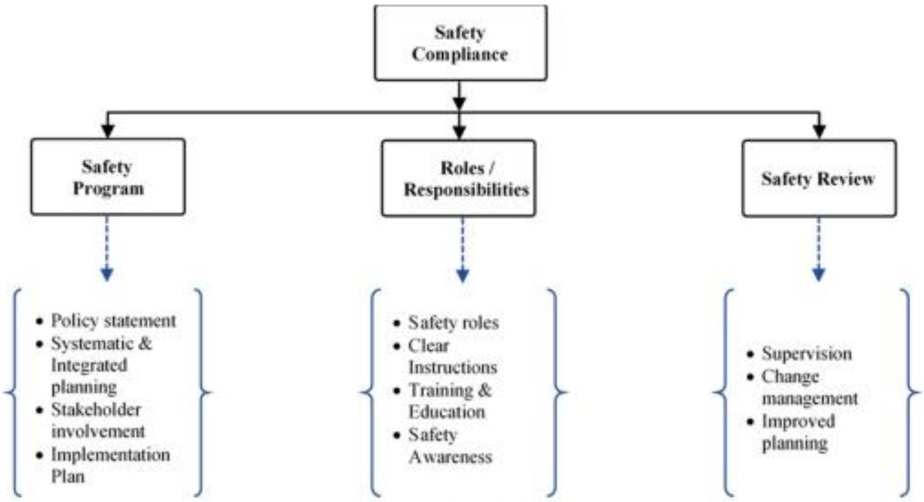

Fig. 11. Safety Compliance Factors.

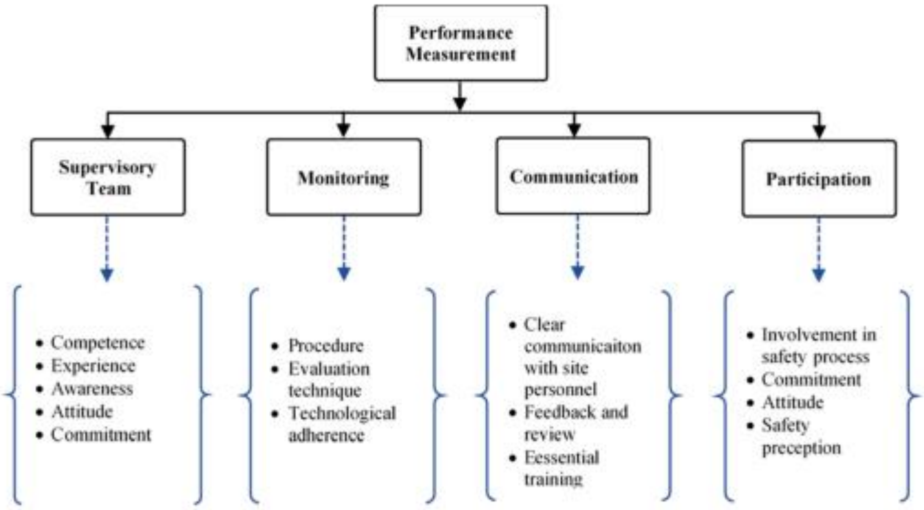

Fig. 12. Performance Measurement Factors.

6.3.1. *Risk assessment*

Risk assessment is recognized as a critical procedure of safety planning as it involves identifying the potential risks that could cause harm to the site personnel (Karimiazari et al., 2011). Identifying and managing the risk from the initial stages of planning, procurement until the construction, and handover is significantly essential to complete the project on time, cost and quality. The researchers have highlighted the importance of systematic risk assessment method for efficient and effective risk management and planning (Serpella et al., 2014). The lack of an effective risk assessment method could lead to several issues during the project. For example, the ineffective risk assessment against the potential hazard or miscommunication could lead to unforeseen events on the construction site, delays, increase in cost or disputes among the parties. The extensive literature review on safety factors revealed that the safety manager's knowledge and experience can have a positive impact on risk assessment. Another factor that helped the safety managers to identify and analyse safety risks is the use of information technology. The use of building information modelling (BIM) has not only helped to identify the safety risks at the pre-construction phase but also lessened the dependency on human perception and knowledge on risk assessment. Fig. 13 below shows the factors involved in risk assessment.

6.3.2. Safety inspection

The site inspection is another essential element of a safety management system and an adequate way to monitor the risks involved, tasks/activities progress, tasks duration, working environment, people and equipment involved in the construction process. One of the research done in China on health and safety management ranked safety inspection as the top third factors affecting safety management (Ashebir et al., 2020). To ensure compliance with the Construction (Design and Management) Regulations (CDM), the principal contractor is bound to arrange an efficient mechanism for regular safety monitoring. The internal inspections are carried out by the contractor itself or a third-party audit to make the construction process safe and productive. Health and Safety inspection is essential for any task that involves risk as they are the source of accidents, such as, work at height, fall protection system, PPE, equipment on the site, scaffold, structural stability and unauthorized access to the site.

In the traditional safety inspection process, manual observations are usually carried out by a safety supervisor or safety specialist on the construction site and after analysis, necessary precautions are considered (Hinze et al., 2013). However, with the advancement in information technology, new technologies for inspection have been introduced by construction professionals. For instance, Tsai et al. (2014) presented a BIM technology for the construction site inspection using the site images generated by BIM. Ashour et al. (2016) used drone technology for gathering site data by taking images at regular intervals. Similarly, de Melo et al. (2017) introduced Unmanned Arial Vehicles (UAV) for the construction site monitoring with enhanced visualization capability. Nevertheless, from the literature review, it is deemed that site inspection should be carried out frequently by a competent safety supervisor based on the safety policy and utilizing the latest technologies that help to identify the hazards precisely (Irizarry et al., 2012). Fig. 14 below shows the essential drivers of safety inspection.

6.4. Safety promotion

Safety promotion is the core of any safety management system as it aims to develop and maintains the safety conditions at the construction site by management, site personnel and everyone involved in the development process. The success of any safety management system is at stake without an effective safety promotion policy. The critical drivers of safety promotions found in the literature are safety culture in the organisation.

6.4.1. Safety culture

The terms 'safety culture' captured the attention of safety experts from different industries involved in the dangerous occurring, such as the construction industry which is well-known for accidents. The safety culture is defined by professionals as an outlook of collective beliefs, values, attitude and behaviours on safety set by an organisation on its entire hierarchy to minimize the exposure to a condition that can cause accident or injury to the members of the organisation (Fung et al., 2005). The wealth of literature on safety culture recognizes it as a leading indicator of the safety management system that helps organisations to reduce the number of accidents in construction sites (Khawam and Bostain, 2019). Subsequently, Hallowell et al. (2013) argued that safety culture is one of the most important investments on the employees as it increases employee awareness and knowledge on safety conditions.

Cooper (2000) conceptualized safety culture in three interrelated aspects: psychological, behavioural and situational aspects. The psychological aspect referred to the organisational values, attitudes and perceptions, the behavioural aspect describes the personal behaviours towards safety, whereas, situational aspects are concerned with the organisational policies, regulations and safety management system. A reputable fact from the research is that the behavioural and psychological aspects of safety culture can be dealt with with adequate training and education programmes (Tudoreanu, no date; Wilkins, 2011). Moreover, the use of information communication technologies (ICT) has improved the learning capability of trainees by creating real-world

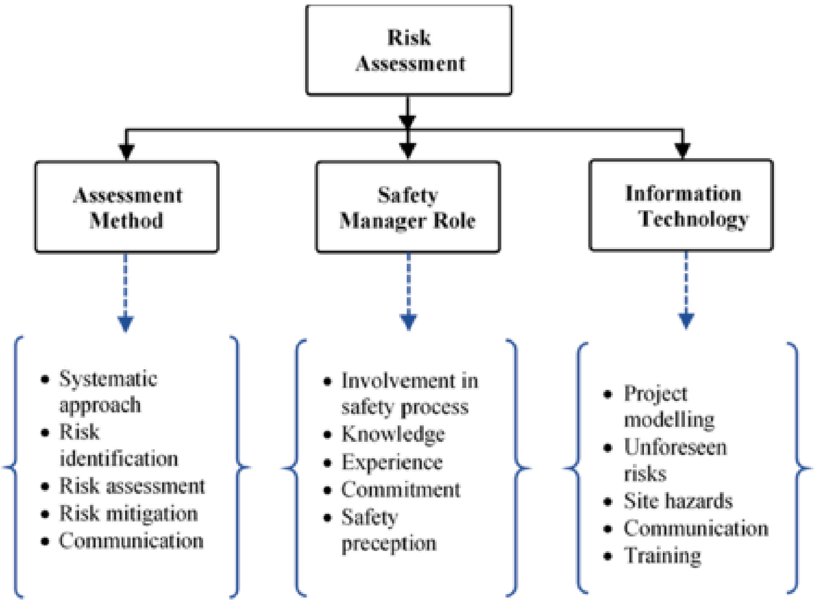

Fig. 13. Risk Assessment Drivers.

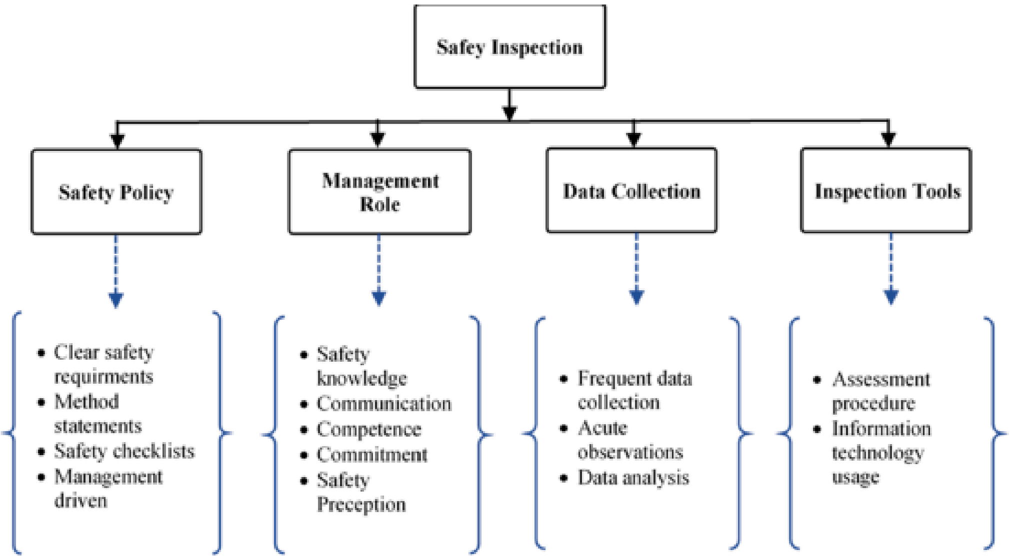

Fig. 14. Safety inspection Management.

scenarios and more visualized learning methods. For instance, virtual reality (VR), Augmented Reality (AR) and other vision-based technologies are quite famous in the construction industry for training purposes (Tudoreanu, no date; Zhao and Lucas, 2015; Li et al., 2018).

Considering Cooper's (2000) model of safety culture, several researchers have explored the factors involved to achieve safety culture at the maximum capacity. Research on safety culture improvement by Machfudiyanto et al. (2019) regarded leadership, safety behaviour, and perception as crucial factors of safety culture. Similarly, another research stated leadership, safety training, commitment and resource allocation as the factors affecting safety culture (Ismail et al., 2009). Fig. 15 below shows the factors involved in the achievement of a safety culture.

7. Conclusion

Accidents on construction sites leading to fatalities, serious injuries and economic cost are a great concern for the construction industry. The pragmatic approach has been used for the research intended to create a Safety Management System framework to improve the safety

Fig. 15. Safety Culture Adoption.

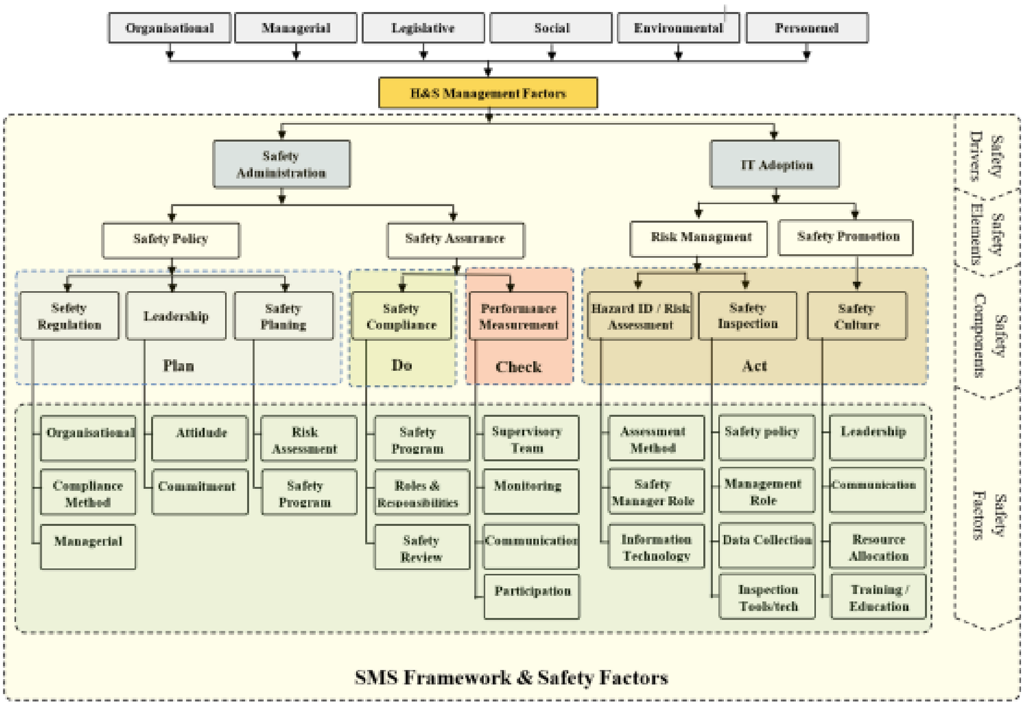

Fig. 16. SMS Framework illustrating Safety Factors with Safety Components.

performance of construction project. Therefore, the research immersed into the safety literature to get an in-depth insight into the occupation health and safety factors involved in the SMS of a construction project to develop a robust safety management framework that complies with all safety factors. This objective was achieved by undertaking an empirical study and a list of sixty-three safety factors was identified from the literature review and classified into six clusters. It has been found that the effective SMS framework requires an inclusive approach over organisational, managerial, legislative, environmental, social, and personnel safety factors to strive for better safety performance.

Hence, the research also proposed to develop an SMS framework to comprehensively analyse and manage the safety performance taking into account the safety factors found in the first stage of the research. Therefore, for adequate safety implementation, the study proposed a safety management system framework developed in three tiers to cope with all safety factors involved in safety management. The first and the primary tier called 'Safety Drivers' channelizes the safety management into two corridors namely 'Administrative' and 'IT'. The administrative route emphasizes safety policy development and assurance whereas, the IT oversees risk management and safety promotions which are called the 'Safety Elements' of the SMS framework. To ensure the success as well as the effectiveness of the SMS framework, another tier was added to the SMS framework called 'Safety Components'. The tier consists of essential steps involved in the safety management and reflects the typical safety management system (plan, do, act and check). Furthermore, the safety factors associated with each safety component has been illustrated in the SMS framework which helps the safety managers to consider safety factors for robust safety management.

This research had some potential limitations which should be noted. The research is entirely exploratory carried out through a literature review, and the recommendations made in the research do not deny or replace any of the existing practices in the industry. Furthermore, the data collection had been performed from the construction literature, therefore, the outcome only relates to the construction safety management. Hence, the study should be regarded as a contribution towards the safety knowledge that can help the construction industry to determine how safety is planned, executed and what factors are involved for the improvement of safety performance. Therefore, the author recommends future researchers to use this study as a proposal for testing the framework and determine the extent to improved overall safety outcomes and performance.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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