PhD Thesis

Robotizing Safety: Prospects and Barriers of Robotic Technology Adoption for Construction Injury Prevention in the UK

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Declaration

I declare that I Innocent Onyeka Obiaigwe is the original author of this PhD thesis, submitted to the University of Salford, UK, for the award of a Doctoral degree in Construction and project Management, it has not been submitted in part or in full for the award of any degree at any University.

Dedication

My PhD journey was ignited by a conference experience in Chicago about two summers ago. During a panel discussion, the topic of future construction robotics captured my attention. This interest was deeply personal, as I had a friend in Nigeria's construction industry who suffered a life-altering injury. This moment catalysed my exploration of how robotics could address widespread construction injuries in the UK. Inspired by my friend's injury, I explored the potential of robotic innovations to revolutionize construction practices and prevent future injuries.

As I explored deeper into this exploration, noting the gaps, I recognized the opportunity for robotics to play a transformative role in challenging the prevailing status quo of construction safety. Despite the abundance of robotic technologies, their adoption in the UK remains relatively low. This disconnect spurred my investigation into how robotics could provide innovative solutions to entrenched challenges within the construction sector, paving the way for safer and more efficient practices.

I therefore dedicate this PhD to my dear friend, the one whose injury is the subtle motivation behind my academic odyssey.

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Completing this PhD thesis has been a monumental journey, filled with countless challenges and triumphs. I owe a debt of gratitude to numerous individuals who have played pivotal roles in this achievement. The path to earning a doctorate is often likened to a marathon, replete with twists, turns, and unforeseen obstacles. From navigating the labyrinthine challenges of a global pandemic to persevering through its aftermath, this journey has demanded resilience, determination, and unwavering commitment. Yet, as this chapter draws to a close, I reflect with profound gratitude on the invaluable support and guidance I have received along the way.

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Furthermore, I extend heartfelt gratitude to my family, whose unwavering support has been the bedrock of my PhD journey. My parents have been steadfast pillars of strength, offering endless encouragement and prayers that have buoyed me through the highs and lows of this pursuit. Their unwavering belief in my abilities has been a source of inspiration, and I am deeply grateful for their unwavering support. To my Elder brother, who has been my steadfast ally since time immemorial, I owe a debt of gratitude for his unwavering encouragement and unwavering support. His belief in my potential has been a constant source of motivation, spurring me on to strive for excellence. I dedicate this PhD to my family in every sense, as their love and support have been instrumental in my success.

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Abstract

The utilization of robots in the construction sector has garnered significant attention in recent years, presenting itself as a transformative technology reshaping traditional construction practices, an industry notorious for its high incidence of injuries and fatalities in the UK. Advancements in robotic and automation systems, coupled with their integration with human workers, are revolutionizing how robots are deployed to address prevalent challenges within the construction landscape. However, despite the potential benefits of robotics, its adoption in the UK remains sluggish. While they hold promise in enhancing safety measures, their efficacy in preventing construction injuries is yet to be fully realized. Considering this context, this research explored both the prospects and barriers associated with robotics adoption within the UK construction industry for injury prevention. Despite the evident need to comprehend and navigate the factors influencing this phenomenon, there is a notable dearth of literature addressing this specific area. The central thesis argues that robotic and automation systems possess the technological capacity to effectively address and mitigate safety risks engendered by construction injuries. However, despite their potential utility, various internal and systemic factors hinder their widespread adoption, thereby constraining their ability to be fully integrated into the industry. This argument is contextualized within the framework of barriers and prospects to discern which holds greater prominence and identify existing gaps. A mixed-method approach was employed to investigate this. This involved the collection of primary data through surveys and interviews, with a total of 54 survey respondents and 10 interviewees participating in the study. A consensus emerged among respondents regarding the instrumental role of robotic technology in the UK construction industry, with several barriers identified mirroring findings from existing literature. Analysis unveiled that the UK construction sector currently occupies a transitional phase, oscillating between inertia and a burgeoning inclination towards accelerated adoption, propelled by ongoing efforts towards robotization and automation; however, adoption remains slow without a clear roadmap for the future of robotics in the UK construction industry. Notably, one of the primary findings suggests that robotic adoption is intricately linked to industry perception, although other ancillary factors also influence the utilization of robotics. In light of these findings, several recommendations emerged as best options to improve the robotic adoption in the UK for addressing construction injuries and safety risks including the saliency of ensuring robotic and automation of the UK construction industry must consider the peculiar and evolving needs of the industry and address the human dimensions implicated in its adoption.

Keywords: Automation, Robotics, Safety, Construction Injuries, Health and Safety, United Kingdom.

List of Abbreviations

AI – Artificial Intelligence

BCG – Boston Consulting Group

BEIS – Business, Energy and Industrial Strategy

CDEI – Centre for Data Ethics and Innovation

CDM - Construction Design and Management Regulations

CPS – Cyber and Physical Systems

DSIT – Department for Science, Innovation, and Technology

ELSA – European Lighthouse on Secure and Safe AI

GHG – Greenhouse Gases

H&S – Health and Safety

HASAWA – Health and Safety at Work Act

HSE – Health and Safety Executive

IFR – International Federation of Robotics

IoT – Internet of Things

LIDAR – Light Detection and Ranging

LIRA - Lancaster Intelligent and Robotic Autonomous Systems Research Centre

MHOR – Manual Handling Operations Regulations

ML – Machine Learning

MMC – Modern Method of Construction

OECD – Organisation for Economic Co-operation and Development

ONS – Office of National Statistics

PwC – Price Water House Coopers

RAS – Robotic and Automation Systems

RIDDOR – Reporting of Injuries, Diseases and Dangerous Occurrences Regulations

ROI – Return on Investment

UK-GBC – United Kingdom Green Building Council

UK-RAS – United Kingdom Robotics and Automation Systems

UKRI – United Kingdom Research Institute

UKVI – United Kingdom Visas and Immigration

WHR – Work at Height Regulations

WIL – Work Integrated Learning

CHAPTER ONE: Introduction

1.0 Introduction

The construction industry has undergone a profound transformation propelled by the integration of cutting-edge technologies, marking a pivotal shift in building practices (Sinclair, 2019). Innovations such as artificial intelligence, robotics, automation, the Internet of Things (IoT), machine learning, and 3D fabrication have revolutionized construction methodologies, with indications pointing toward further advancements in the field (Zhou et al, 2020). Recent strides in robotic design and software systems have reshaped both on-site and off-site construction processes, facilitating innovative design solutions and promoting cleaner, more sustainable practices (Wang et al, 2019; Newman et al, 2020).

Amidst these advancements, a crucial consideration revolves around the role of technology in preventing construction-related injuries. Traditionally, construction activities have posed inherent risks due to their labour-intensive and high-risk nature (Brock, 2016). However, studies suggest that automation and robotics hold promise in mitigating these risks, particularly concerning falls, over-exertion, and strains (Anagha & Xavier, 2020; Anwer et al, 2021). Yet, challenges persist, including the initial costs associated with adopting these technologies, their transferability, uptake, legal and regulatory loopholes that serve to hinder their widespread implementation (Bowman, 2020).

Recent studies have shed light on the pivotal role of technological advancements in shaping contemporary construction practices (Xu et al, 2022; Moore et al, 2023). These investigations highlight three fundamental factors influencing the utilization of technologies like robotics in construction projects. Firstly, the level of knowledge and awareness surrounding these innovations and the extent to which they are embraced play a crucial role (Martens et al, 2021). Secondly, the selection of technology and its associated costs are key considerations when integrating it into the construction domain. Lastly, there's a growing focus on the environmental and sustainability implications of these technologies, spurred by the increasing discourse surrounding climate change. This necessitates a holistic approach that evaluates the environmental impact of innovations throughout their lifecycle, from inception to disposal, including waste management and recycling efforts (Brandon et al, 2022; Wang et al, 2023).

Construction sites frequently witness overexertion injuries, which account for over 25 percent of work-related incidents, stemming from activities like heavy lifting, repetitive motions, and muscle strain (Greene et al, 2021). These injuries encompass a range of ailments, including back injuries, repetitive strain injuries, and forceful exertion injuries, often exacerbated by prolonged sitting, exposure to extreme temperatures, and equipment operation (Griffins et al, 2021). In addition to falls, overexertion injuries represent a significant hazard in the construction sector, often resulting from repetitive tasks (HSE, 2022). However, advancements in robotics offer promising avenues for injury prevention (Silknonnen et al., 2022). The demanding and repetitive nature of construction tasks heightens the risk of musculoskeletal disorders, including ligament and tendon wear and tear (Griffins, 2014). Associated injuries such as sprains, strains, carpal tunnel syndrome, and osteo and hip dislocations are also prevalent, influenced by factors such as physical exertion, age, and individual tolerance levels (Everett, 1999; Schneider, 2001; Anagha & Xavier, 2020; Anwer et al., 2021). Moreover, hazards linked to moving machinery and vehicular accidents further compound these risks, highlighting the multifaceted nature of injury prevention in construction environments.

The question of whether robotics should supplant human labour in construction remains contentious amid the emergence of new technologies. While some scholars advocate for a hybrid approach that combines human expertise with machine capabilities to mitigate risks and enhance efficiency (Machido et al, 2021; Karl et al, 2020), others argue for full automation to address safety concerns and reduce physical strain (Denver et al, 2020; Sinclair et al, 2021). This debate intersects with broader considerations of unemployment, economic viability, and regulatory frameworks governing technology adoption in the construction sector (Malak et al, 2021; Moore et al, 2019).

The symbiotic relationship between humans and machines within the construction sector presents a multifaceted paradigm. While machinery serves as a force multiplier, augmenting human capabilities and mitigating risks associated with physical strain and errors, the indispensability of human involvement remains salient (Wang et al, 2021). Although traditional machinery such as robotic arms necessitates human operators, recent advancements have ushered in autonomous technologies, marking an evolutionary change in the incorporation of advanced robotics in construction (Denver et al., 2020; Sinclair et al., 2021). However, these technological innovation prompts a critical inquiry into the socio-economic ramifications of automation, with scholars grappling with its potential to mitigate unemployment and labour market disengagement (Malak et al., 2021). This discourse underscores a dialectic between efficiency optimization and economic rationalization, encapsulating broader concerns surrounding labour dynamics and technological disruption (Moore et al., 2019). As the construction domain navigates these complexities, achieving equilibrium between human expertise and technological innovation emerges as a key imperative, shaping the application of safety protocols and operational efficiencies within the construction industry. This is against the backdrop that the successful integration of robotics hinges on a plethora of factors such as regulatory compliance, workforce expertise, and industrial infrastructure (Mahmud et al, 2020). Moreover, concerns persist regarding the potential paradox of safety, as improper use or inadequate training may exacerbate health and safety risks on construction sites. Studies opine that the pivotal issue surrounding robotics in construction revolves around balancing safety imperatives with technological advancement and economic considerations (Bakare et al, 2020).

Besides the cost implications of adopting robotic technology, another critical consideration pertains to whether these machines introduce a safety paradox in the construction environment. Improper usage or lack of adequate training and supervision can exacerbate health and safety risks. Therefore, the central issue surrounding robotics in construction revolves around the extent to which robotic technology should be embraced to mitigate construction injuries and maximize its potential benefits. This necessitates an evaluation of its feasibility, efficacy, and potential risks, as well as an exploration of key prospects and opportunities for its utilization in the construction sector.

The central plank of this thesis asserts that advancements in robotic technology offer transformative potential in preventing construction-related injuries. However, the feasibility of this proposition is contingent upon various factors, including the accessibility, adoption rate, and design of such technologies, as well as the regulatory framework governing their implementation within the UK construction sector.

1.1 Construction Industry in the UK

The UK construction industry plays a pivotal role in the nation's economy, boasting a substantial contribution to the Gross Domestic Product (GDP) and serving as a major employer. According to UK Government data from 2023, the construction sector's GDP contribution surged from 5.5% in 2018 to 7%, amounting to an annual revenue of £110 billion. Presently, approximately 9% (1.4 million) of the UK workforce is engaged in construction-related activities. The robust growth of the construction market, estimated at £402.3 billion in 2023, underscores its significance, with the residential construction sector emerging as a dominant force.

The remarkable surge in the UK construction industry's value can be largely attributed to the substantial expansion of public sector projects since 2018. This surge has led to an exponential increase in investment, reaching £2.69 billion compared to £750 million previously. Despite facing setbacks due to the global pandemic and the repercussions of Brexit, the construction sector has witnessed a notable rebound. New construction company registrations have surged by over 5.2%, reflecting a growth rate of 5.5% (HSE, 2022). Predictions indicate that building construction, valued at £239.4 billion, will continue to spearhead market expansion. Furthermore, the sector is poised for rapid expansion over the next decade, fuelling job creation and fostering innovation. Key segments within the UK construction landscape encompass commercial, residential, industrial, infrastructure, energy, utilities, and institutional construction, each offering specialized services tailored to diverse market demands. Detailed exploration of these sectors and their respective contributions forms a critical aspect of this thesis analysis.

Table 1: Types of construction and planned/ongoing government investment in the UK

Types of Construction	**Coverage**	**Planned and Ongoing Government Investment**
Residential	Single-family housing and multi-family housing	The government's focus on the construction of 180,000 affordable homes in the country by 2026, with an investment of GBP11.5 billion ($14.2 billion)
Infrastructure	Rail infrastructure, road infrastructure, and other infrastructure projects	660 projects and programmes across the public and private sectors. £164bn planned for investment by 2024/25 £700-775bn of planned and projected investment over the next 10 years £64bn worth of investments, including MMC. £22bn of forthcoming infrastructure procurements
Energy and utilities construction	Electricity and power, oil and gas, telecommunications, sewage infrastructure, and water infrastructure	Investments in renewable energy projects in line with the government's aim to generate 95% of the country's electricity from low-carbon sources by 2030 will drive the sector growth during 2025-2028.

Commercial construction	Leisure and hospitality buildings, office buildings, outdoor leisure facilities, retail buildings, and other commercial construction.	Several commercial construction projects are already underway in the UK.
Industrial construction	Different types of plants, including Chemical and pharmaceutical plants, manufacturing plants, waste, material, and metal	Investments as part of the Advanced Manufacturing Plan, unveiled in November 2023 and include an allocation of funds for the automotive industry and the aerospace industry.
Institutional construction	Educational buildings, healthcare buildings, institutional buildings, research facilities, and religious buildings	Several institutions in the UK are taking on large construction projects on-site.

Source: Author's adaptation from data obtained from the GOV.UK (2023)

Despite the technological advancements and economic potential of the UK construction sector, it remains among the most hazardous industries, characterized by a concerning number of injuries and fatalities (Newman et al., 2020). Recent statistics from the Health and Safety Executive (HSE) UK reveal that a staggering 42% of workplace fatalities, out of 142 recorded incidents, occurred within the construction industry alone (HSE, 2022). Predominantly attributed to falls, slips, and various workplace hazards, this alarming statistic underscores the persistent risks inherent in construction activities. Moreover, while the reported fatality rate has declined over the years, long-term trends suggest that instances of near misses and injuries may surpass the reported figures, indicating a potential underestimation of the true extent of risks (HSE, 2022). Additionally, the introduction of new technologies in the construction sector has brought forth novel health and safety concerns, necessitating comprehensive measures to mitigate risks associated with their integration. This phenomenon encapsulates the paradox of innovation, wherein advancements aimed at reducing the risks of injuries from repetitive tasks may inadvertently introduce new health and safety hazards if not accompanied by adequate safeguards and protocols.

A 2022 report by the Health and Safety Executive (HSE) sheds light on workplace fatalities in the UK, revealing that the construction sector has consistently reported a higher five-year average of fatal injuries compared to other sectors such as Agriculture, Forestry, Transportation, and Manufacturing. Despite a gradual decline in total reported cases of injuries and fatalities over the past decade, the trend has not plateaued. Out of the 145 workers killed in the workplace in the 2022/2023 period reported in the Reporting of Injuries, Diseases, and Dangerous Occurrences Regulations (RIDDOR), construction accounted for

48%, with 45 fatal injuries. Falling from height constituted 40% of these injuries, followed by being struck by a moving object and incidents involving moving vehicles, which accounted for 29% and 20% respectively (HSE, 2022). Similarly, data from previous years indicate a persistent trend, with the construction industry consistently accounting for a significant portion of reported injuries and fatalities. In 2020/2021, the construction industry represented 42% of reported cases, while 40% of reported fatalities in 2019/2020 were also attributed to the construction sector (HSE, 2020). This persistent pattern underscores the construction industry's status as one of the riskiest sectors in the UK, characterized by a higher incidence of workplace fatal injuries and fatalities.

The UK construction industry grapples with a myriad of challenges that heighten the risk of occupational injuries and fatalities. One prominent concern is the shrinking workforce, driven by factors such as an aging population, escalating costs of supplies and labour, economic volatility, and evolving environmental regulations (Sinkonnen et al, 2021; Graham et al, 2020; Alaba et al, 2023). Presently, the UK has over 10 million individuals aged 65 and above, constituting 18% of the population. Projections indicate that the population aged 65-79 will surge by an additional 10 million over the next four decades (ONS, 2022). Over the past two decades, the Office for National Statistics (ONS) reports a substantial uptick in the number of workers aged 50, rising by nearly two-thirds from 6.6 million to 10.6 million. Notably, the construction industry grapples with an aging workforce more than any other sector, with nearly 20% expected to approach retirement age in the next 5-10 years (ONS, 2022). This demographic shift poses challenges in terms of essential skill retention and elevates the risk of injuries stemming from age-related health issues. While older workers bring valuable attributes like a strong work ethic and institutional knowledge (Erikson et al., 2021), they face heightened risks in physically demanding environments such as construction sites, where the pace is often fast-paced and physically demanding, increasing the likelihood of workplace incidents.

1.2 Research Rationale

Recent studies have brought into question the feasibility and implications of integrating new technologies within the construction sector (Martens et al., 2020; Reid et al., 2021). The adoption of such technology hinges on various factors, including regulation, uptake, and upfront cost, and desire to adopt among stakeholders (Mortens et al., 2021). Regulation is a critical aspect, determining whether these technologies meet the requisite standards for use in the UK, with considerations extending to compliance with existing legislation and government policies. While the UK lacks a specific unified law governing robotics, regulations such as the Data Protection Act and GDPR, alongside health and safety legislation, guide their implementation (UK GOV, 2021; Deloitte, 2022). Core principles encompassing safety, transparency, fairness, and accountability dictate the extent to which these technologies are embraced, utilized, and implemented within the construction industry. Regulation stands as a pivotal factor dictating the pace and scope of robotics adoption within the UK, intertwined with geopolitical dynamics, especially among the UK's digital competitors.

The slow uptake of new technologies in the UK construction sector remains a pressing concern, hindering the realization of cheaper, faster, and smarter services, as outlined in a 2018 UK GOV report (Boris et al., 2021). Despite advancements in technology, the construction industry lags behind sectors like healthcare, security, education, and finance in technology adoption rates (Casleigh et al., 2018; Ajagbe, 2019). Currently, the UK's technology adoption rate stands at around 10 percent, lower than the Organisation for Economic Co-operation and Development (OECD) average of 14 percent and significantly behind East Asian and Nordic countries at 22.5 percent (Arntz et al., 2019). Particularly in construction, the UK trails behind leading industrial nations such as Korea, Singapore, Japan, China, and Germany in robot adoption, with less than 85 robots per 10,000 employees compared to other leading countries (Fusch, 2021)

A House of Commons Science and Technology Committee report in 2016 emphasized the importance of the UK embracing AI and new technologies in the construction domain, yet while there have been some significant leaps, the progress is still slow (Ford et al., 2022). Factors contributing to the slow adoption of robotics in the UK construction sector include the industry's vulnerability to cycles of boom and bust, resulting in mismatched long-term expectations post-deployment (Olsen, 2018). While some have labelled this phenomenon as a "technology winter," newer perspectives suggest it's an inherent part of technological advancement, highlighting the need for industries to continuously evolve with new technologies rather than stagnate (Mahmud, 2021).

The literature highlights numerous benefits associated with the integration of robotics into the construction sector, including enhanced efficiency, reduced injury rates, augmented collaboration between humans and robots, lowered labour costs, and the facilitation of novel construction methods and innovations (Bogue et al., 2018; Laucombe et al., 2020;

Greene et al., 2021). However, amidst these advantages, a recurring concern revolves around the cost-effectiveness of robotic adoption, given the associated expenses and barriers to uptake. Studies by Quezeda (2016) and Bogue et al. (2018) have identified various factors hindering widespread adoption in the UK. These include challenges in supporting new technologies to meet low-carbon energy objectives, the need to commercialize UK robotic inventions amidst global competition for investment, the necessity for robust innovation support to drive automation as a key growth area, and the importance of government engagement and support. These issues are further dissected later in the thesis.

In addition to the aforementioned challenges, Mahbub (2019) delineated five additional factors currently constraining the uptake of robotic technology. These encompass robot-oriented design, automation capabilities, variations in robot types, the industrialization of robotics, and the dynamics of the construction site. The categorization posited by Mahbub suggests that the design of robots may not universally conform to jurisdictional standards, with differing regulatory requirements across countries. This, in turn, intersects with the suitability of robot types for specific construction environments. Moreover, the pace of automation adoption varies among nations due to underlying political and economic complexities. This dichotomy is akin to the concept delineated by Olabode et al. (2021) as "slow uptake" versus "fast uptake." The former denotes a calibrated and staggered approach to technology integration to mitigate unemployment and address broader macroeconomic concerns, while the latter signifies rapid assimilation of technological innovations into industrial processes such as with Japan, China in the manufacturing sector. One of the main issues identified has been the rebound effect which explains a situation where a contractor's inclination to use robotic innovations is limited by budget, scheduling and time including the desire to stick to tried and trusted methods to delivery of construction services instead of giving innovative approaches a chance (Cheng et al, 2022).

The literature highlights several macro-level factors that influence the adoption of technology on a broader scale, including labour market performance, prevailing rates of automation, the availability of skilled workers, public attitudes, and economic structures. About public attitude, a report by the Royal Society UK identified public attitudes towards machine learning and new technology as a contributory factor limiting its uptake. The report mirrored public attitudes as “Participants took a broadly pragmatic approach, assessing the technology based on the perceived intention of those using the technology; who the beneficiaries would be; how necessary it was to use machine learning, rather than other approaches; whether there were activities that felt inappropriate; and whether a human is involved in decision-making. Accuracy and the consequences of errors were also key considerations" (Royal Society UK, 2017).

Although recent surveys indicate shifts in public sentiment, underlying concerns persist. According to a 2023 report by the Department for Science, Innovation, and Technology (DSIT) UK, as part of the Centre for Data Ethics and Innovation (CDEI) Public Attitude to Data and AI tracker survey, there has been a noticeable evolution in public perception regarding the impact of data-driven technology, including AI. People exhibit greater comfort with these technologies in specific contexts, such as improving health outcomes, IT systems, and education (DSIT cited in UK GOV, 2023). However, the report highlights enduring apprehensions among the public, particularly concerning the risk of job displacement, the potential erosion of human creativity and problem-solving skills, and ongoing concerns about data security and breaches. These factors collectively shape the level of robotic adoption within various industries. However, an additional issue pertains to research gaps in the implementation of robotics in construction. While existing studies have identified shortcomings in robotic integration, there remains a dearth of research examining this issue from the perspectives of stakeholders, regulatory bodies, and industry stakeholders.

At the core of the adoption paradigm lies the regulatory environment, which serves as the central pivot around which all aspects of technology uptake revolve. Surrounding this core are concentric circles representing research, industry, stakeholders, awareness, and the global-local environment, all of which contribute to the viability of robotic adoption. However, much of the existing research has focused on peripheral factors, with limited exploration of the intersection between the inner regulatory environment and the outer contextual factors.

On the subject of research, current efforts in Robotics and Artificial Intelligence (AI) are primarily driven by the private sector, a departure from the government and university-led initiatives of the 1950s. While this shift has seen a surge in investment over the past decade, it has also raised concerns regarding the increasing influence and accountability of 'Big Tech' in steering technological innovation (Graham et al., 2019). Furthermore, despite the UK's early leadership in AI research and its Industrial Strategy's ambition to champion world-class innovation in the forthcoming decades, the efforts of nations such as China, Japan, Malaysia, and Australia currently overshadow these aspirations (Miazo et al., 2017).

Regrettably, there has been a notable deficiency in research efforts within the UK to address this disparity (Dristas & Soe, 2018). While there is a standing committee in the UK House of Commons to examine the short and long-term implications of new technologies in the UK, there has been no clear agenda on what the level of uptake should be, particularly for the construction sector (Linner et al, 2020). Moreover, surveys indicate a scarcity of laboratory facilities dedicated to robotics innovation in the UK, thereby constraining potential research into automation technologies and the experimentation of live construction methodologies (PwC, 2021). It is noteworthy that there are several businesses innovating robotics in the UK such as the Bristol Robotics Laboratory that manufactures bionic arms, the Small Robot Company, Ocado, Tharus, (this is besides the growing number of universities across the UK investing in robotics and automation), many are failing to attract large scale investment and successful commercialization (GOV.UK, 2019).

This research gap underscores the necessity for further investigation into this area to comprehensively understand the factors influencing robotic adoption for injury prevention in the UK construction industry. Such insights are crucial for developing targeted interventions and strategies to promote the effective utilization of robotics in enhancing workplace safety and mitigating construction-related injuries. Understanding the factors impeding the uptake of robotic technology in the construction industry in the UK is vital. Not only is this an underappreciated area in research, but assessing it would paint a clearer picture of the potential utility of robotics for the prevention of injuries among construction workers. This entails an appraisal of how the UK is faring compared with other countries in the adoption of robotic technologies and a consideration of factors (internal and external) impeding the uptake of the technology in the construction industry.

Several studies have examined the potential utility of robotics for the automation of repetitive construction tasks that increase the incidence of injuries and other risk exposures such as laying of bricks, concrete mixing, reinforcements, plastering, loading and unloading, including handling of hazardous wastes and chemicals, navigating pipe networks, repair of underground pipes and in trenching (Aghimien et al, 2019; Brock, 2018; Arntz et al, 2020). Innovations such as 3D printing machines are capable of doing most of these functions with greater precision, design outfitting, and reduce the cost of labour by more than 90 percent with the added advantage of increased productivity and efficiency (Wang, 2020). For instance, SAM (a conveyor mortar pump and a robotic arm developed in the United States), a bricklaying machine, has the output capacity of laying 3,000 bricks a day, which is six times more than a skilled tradesperson (Grant, 2020). Likewise, the Australian Hadrian X is a truck-mounted robot that has been successfully deployed for outdoor test builds and the Ekso vest (a high-tech exoskeleton developed by Ekso Bionics) has been used by construction companies in the United States to support worker's arms during heavy lifting and in the handling of power tools. Studies have also explored the role of assistive device as an innovative ergonomic intervention to reduce construction related injuries and other types of uses including rehabilitation and military applications (Yan et al, 2018; Federici et al, 2020). The utility of these robots is due to their automated inherent capability to assist or autonomously carry out dangerous, repetitive, and labour-intensive construction works with greater efficiency and accuracy (Pan et al, 2020; Owolabi et al, 2018) In addition, robotics are expected to reduce the incidence of falls, risk exposure to hazardous chemicals, moving vehicles, and extensive use of physical labour (Liu et al, 2020).

1.3 Research Questions

The research undertaking was guided by several questions that formed the analytical premise for the investigation of this thesis. The questions are as follows:

i. What is the current state of robotic technology adoption in the UK construction industry?
ii. What are the prospects and main barriers affecting its uptake in preventing construction-related injuries?

1.4 Research Aim and Objectives

One of the main underlying aims of this study is to determine the factors affecting the viability and uptake of robotic technology in the construction industry in the UK. Specifically, the study will explore the following:

i. To comprehensively examine the main factors shaping the development and uptake of robotic technology in the UK building construction industry
ii. To systematically identify, categorise, and prioritise identify, categorise, and rank the pivotal factors limiting the adoption of robotics for Health and Safety enhancement within the UK Building Sector
iii. To investigate option to improve robotic technology adoption in the UK construction industry.
iv. To advance a comprehensive framework to address unique challenges of H&S applications within the UK construction sector, facilitating the seamless assimilation of component RAS.

1.5 Justification of Research

In an era of rapid technological advancement, the exploration of innovative solutions to mitigate construction-related injuries and fatalities becomes increasingly imperative. This urgency is underscored by the high-risk nature of construction work and the persistently low adoption rates of crucial robotic technologies designed to address these risks (Wang et al., 2021; Cheng et al., 2022). Despite the ongoing digital transformation across various industries, studies reveal a slower pace of digitization within the construction sector (Wu et al., 2020). While the construction industry presents unique challenges, viable robotic solutions exist, albeit with acknowledged limitations that may hinder widespread adoption, such as the size of firms and initial costs associated with implementation (Delgado et al., 2019; Darlow et al., 2022; Capitani et al., 2021; Boulos et al., 2021).

Numerous studies have examined the utility and applicability of robotics in construction, yet there remains a notable gap in research focusing on the specific context of the UK construction industry and the factors influencing the scalability of these innovations (Wu et al., 2020). Consequently, there is a pressing need for further study into the feasibility and potential barriers affecting the adoption of innovative technologies within the UK construction sector. However, there remains a paucity of studies that explore the viability of these innovations for the UK construction industry and what are the factors affecting its uptake at a large scale. Some studies have come close to examining this phenomenon (Greene et al, 2015; Owolabi et al, 2019; Mariam et al, 2019; Osimhen et al, 2020, Gleed, 2021), but the findings fall short of providing robust data of evidence to provide the basis for conclusions. Also, existing literature has not considered the broader factors that are affecting the uptake in the UK, especially from the perspective of stakeholders in the industry. The lack of primary data highlights the gap in the literature and the saliency of further study to shed light on this critical issue particularly as new technologies emerge, and the construction industry finds itself at the epicentre of these revolutionary changes with attendant implications for the future of construction.

1.6 Organisation of chapters

This introductory chapter sets the stage for the research, emphasizing the need for further investigation to establish analytical parameters for the remainder of this thesis. It delves into the background, serving as the foundational premise for the thesis's objectives. The research question, objectives, and rationale are articulated, along with the thesis statement that guides the analytical framework.

To explore the analytical parameters of this thesis that provide an ambit to answer the research questions and explore the research objectives, the thesis is structured into seven chapters.

Chapter One: Provides the analytical background of the research, it establishes the main purpose for the research investigation, the scope of the study, the significance of this research to the literature, and the key gaps in the literature. This was important in setting out the boundaries of this study providing context for deeper exploration of the research variables that drive the research undertaking and outlining the fundamental questions that guide the research inquiry on the viability of robotic technology uptake in the UK in the prevention of construction injuries.

Chapter Two: This chapter examines the different types of robotic technologies and their application in the construction industry, to provide an ambit into the key factors affecting adoption on a large scale. The chapter delves into the intricacies of robotic technology adoption within the UK context, aiming to uncover the primary factors shaping its architecture and uptake. This examination is essential for gaining insights into the current landscape. The chapter also evaluates theories and underpinning concepts relating to robotic technology innovation and utilization in the construction industry.

Chapter Three: This chapter is a situational analysis of the construction industry in the UK. It examines the current issues that shape and continue to shape the industry including Brexit, innovation, regulation, geopolitics, and broader issues that influence the construction industry in the UK. This also includes a brief history of the industry, the various types of construction industry, and the current stakeholders in the industry. This section is important to provide the analytical bandwidth to properly analyse the issues relating to robotic adoption later in the thesis.

Chapter Four: This chapter takes an analysis of the different injuries in the construction industry and its nexus with robotics. It triages the main injuries, classifies them in order of occurrence, and analyses how robotic technologies are affecting the preponderance of injuries and the gaps in the use of these technologies for these injuries. Another aspect of the analysis covered in this section is the exploration of the literature on factors affecting the uptake of this technology in the prevention of these injuries. This is assessed from the lens of construction safety.

Chapter Five: Discusses the methodology of the research. This chapter is an in-depth discussion of the research design and the rationale behind the chosen research design for the synthesis of findings. It also discusses the limitations of the study.

Chapter Six: Takes a deep exploration into the findings of the study. It discusses the critical findings of the thesis following the presentation of findings, detailed analysis, and interpretation of the results. The findings of the study from the primary data collection process were conducted in this chapter shedding light into the research undertaking.

Chapter Seven: This chapter concludes the research. It also re-litigates the research findings and provides options for improving robotic adoption in the UK. The implications for future research and development in robotics are also discussed and recommendations are put forward for best options for robotic adoption including a proposal for the road mapping the future of robotic and automation systems in the UK.

CHAPTER TWO: Conceptual and Theoretical Nexus: Robotics and Construction

2.0 Introduction

This chapter assesses the foundational concepts essential to this thesis. Conceptually defining key terms is crucial as it provides a clear context for analysing the rest of the thesis. Moreover, these conceptual frameworks serve as the backbone of the study, offering valuable analytical tools for establishing research questions and objectives. By delineating these concepts, it becomes easier to navigate the various variables under scrutiny.

Following the introductory part, the conceptual terms implicated in this study is assessed to provide clarity and the ambit for subsequent analysis undertaken in the rest of the thesis.

Next, is the theoretical review of related theories that provide plausible explanation to factors limiting the adoption of robotic technology and the limitations of these theories as it relates to the research phenomena. In the third part, this thesis undertakes an analytical excursion into the empirical literature on robotic technology, examining its types, benefits, limitations, and applications within the construction industry. It explores emerging robotic technologies and their integration with modern and smart construction practices, focusing on their impact on the UK construction industry. This chapter serves as a critical foundation for the subsequent analyses, situating the meaning, types, and utility of robotics within analytical parameters. By doing so, it sets the stage for a deeper exploration in the following chapters, particularly concerning the dynamics of robotics and safety in the UK construction industry.

2.1 Robotics

Construction robots made their debut on building sites, initially employed to enhance the quality and assembly of modular homes (Misuwa, 2015). The evolution of robotic systems for construction reached its peak during the 1960s and 1970s (Ajoudani et al, 2018). Since then, various types of robotic technologies, including exoskeletons, 3D printing, and automated fabrication systems, have been developed and implemented in construction projects. However, there remains a lack of consensus in the literature regarding the definition of construction robots (Wang et al, 2020). Some studies (Callum et al, 2019; Pan et al, 2020; Zhiyong and Kirwan, 2020) describe construction robots as "sophisticated and intelligent machines with robotic features." Joiner (2018) conceptualizes robotics as "Machines capable of semi-autonomous operation based on programmed algorithms to execute complex and repetitive tasks with enhanced efficiency and accuracy. They possess sensory awareness, resilience, and are deployable in hard-to-reach areas. Capable of identifying, assessing, and analysing risks in dynamic and hazardous construction environments, they reduce the risk of safety hazards and work-related fatalities."

However, recent innovations in AI and its expanded application in the construction industry have broadened the scope of this definition. This includes robots capable of autonomous operation based on pre-programmed algorithms, as well as robots that mimic human actions and appearance. Hasegawa and Maeda, who conceptualized the development and systems engineering process for construction robots, argue that the utility of robotic technology is contingent upon iterative and linked steps, as well as a comprehensive understanding and definition of the dynamic contexts surrounding each system, before any informed understanding and management of associated systems can be achieved (Hasegewa & Maeda, cited in Bock and Linner, 2015).

Robots play a diverse range of roles within the construction industry, encompassing building, demolition, and site inspection tasks (Cheng et al, 2021). Recent innovations in robotic technology enable swift operations, including concrete mixing and pouring, repetitive task execution, and operation in hazardous or inaccessible areas. Notably, advancements have led to the creation of demolition robots capable of safely and efficiently dismantling structures (Greene et al, 2021). These robots can be controlled remotely or manually and are adaptable to various tools. Moreover, inspection and surveillance robots equipped with cameras and sensors facilitate data collection and defect detection during site inspections (Wu et al, 2022). The emergence of humanoid robot technology has expanded the traditional applications of robots in construction. For instance, robots like the Japanese HRP-5P exhibit a blend of speed, flexibility, power, and precision, along with autonomy capabilities enabled by advanced actuator and control systems (Delgado et al, 2018).

Recent studies highlight the emergence of robots integrating aerial approaches for automated functions, power-augmenting exoskeleton robots, collaborative bots, and humanoid robot technology (Newman et al, 2020). Humanoid robots, designed to resemble the human form, have a broad spectrum of capabilities. They can undertake manual construction tasks such as bricklaying, concrete pouring, and painting, and interact with human workers by providing assistance and guidance. Furthermore, they possess dexterity and precision akin to humans, enabling them to work swiftly and accurately, even in hazardous environments (Capitani et al, 2021). Additionally, humanoid robots have shown promise in emergency response scenarios like search-and-rescue operations in collapsed buildings.

However, despite their potential, humanoid robot technology is still in its nascent stage of development and has yet to be widely adopted in the construction industry (Vashi et al, 2021). Robotic technologies are revolutionizing various aspects of construction and production systems, enabling them to perform a multitude of tasks. For example, the Husqvarna DXR remote control robots are versatile tools used for concrete finishing, bricklaying, demolition, painting, and lifting (Zhang et al, 2019). The potential applications of robotics in the construction and infrastructure sectors are expanding to include handling toxic wastes, surveying, assembling, fabrication, and working in confined spaces. These activities are commonplace in the workplace and often pose risks of injuries and health and safety concerns (Olsen, 2018).

Despite the evident benefits, the adoption of robotics in construction lags behind other sectors like services and manufacturing (Brock, 2018). Studies by Liu (2018) and Zhou (2019) suggest that the advancement of robotics in construction is not proportionate to its current level of uptake. Sousa and colleagues (2018) conducted a survey of 11 construction companies and government agencies in Europe, revealing that concerns about job displacement, implementation costs, and associated commercial and technical risks hindered the adoption of robotics and automated systems. Moreover, Zhang et al. (2019) note that the construction industry has been slow in embracing not only robotics but also new technologies in general. However, Wallace (2017) argues that automation and robotics are indeed reshaping the sector significantly and will play a pivotal role in its future development. Previous studies (Gauseimeier et al, 1998; Kale and Arditi, 2010) have made efforts to analyse the future utilization of construction robotics. However, they fall short of systematically exploring likely future scenarios and alternatives for their use. Currently, there is a scarcity of research examining the early-stage application of construction robots in engineering contexts, and many predictions regarding their potential use are based on vague assumptions (Zhang et al, 2020).

Furthermore, the field of construction robotics is not yet well-established, with a lack of robust data from previous applications and scenarios in the construction space (Pan et al, 2020a). This gap necessitates the development of new tools for assessing the potential applications of robotic technology. Additionally, there remains a lack of consensus in the literature regarding the definition of a construction robot. While some studies describe them as sophisticated and intelligent machines with robotic features, the integration of AI into construction robotics has expanded the scope of this definition. To facilitate the analysis of system requirements, design, and development of construction robots, clear categorization is essential (Bock, 2015). Hasegawa & Maeda, who conceptualized the development and systems engineering process for construction robots, argue that the utility of robotic technology is contingent upon iterative steps and a comprehensive understanding of the dynamic contexts surrounding each system (Hasegawa & Maeda cited in Bock and Linner, 2015).

2.2 Robotic Evolution

Industrial robots first emerged in the 1950s and have since undergone extensive advancements, becoming ubiquitous in today's construction sector (Reece, 2018). Although their utilization did not become widespread until the 1980s, initially designed to address skill and labour shortages in Japan, their impact on the manufacturing industry became increasingly evident over time. As their effectiveness became more apparent, their adoption expanded, and robots have since become integral to the industrial landscape (Wood et al., 2014).

The concept of robot evolution remains a focal point in the literature, reflecting the dynamic nature of robotics and technological innovations. As technology advances, so do changes in functionality and the introduction of new models and iterations in the construction sector (Maartens et al., 2019). Since the industrial revolution, machines have undergone significant transformations, evolving from aiding in manufacturing processes to reducing manual labour and accelerating production on an industrial scale (Nolfi, 2021). This evolution has witnessed the widespread use of robotic technologies across various industrial functions, including recent advancements in autonomous capabilities (Floreanno, 2018). Scholars envision this century as the era of robotics, given the rapid proliferation of robotics systems in today's world and their integration into the design process (Schranz, 2020; Barelli, 2019). Amidst these advancements, a central theme in the literature is the role of robotics in driving future design, manufacturing, and production processes autonomously, guided by programmed algorithms, without direct human intervention (Liu et al., 2021; Wang et al., 2022).

Robotics has progressed significantly, with continuous innovation integrating high-end technologies such as sensors, actuators, software, and AI systems, driven by the rise of digitization. These advanced robots are adept at reducing repetitive and strenuous tasks, thus minimizing the number of man-hours required and lowering the margin of error (Barken et al, 2018). As software technology integrates deeply into robotics design, the potential for robots to operate with enhanced resilience in the construction sector becomes increasingly relevant (Brambilla et al., 2021). Smart robots are already demonstrating this capability in sectors like manufacturing and healthcare, where they perform complex tasks, including assisting in surgical procedures, with impressive outcomes. Robotic sensing has become indispensable, employing a variety of sensors for precise operations. Commonly utilized sensing solutions include safety 2D and 3D laser scanners, LiDAR for obstacle detection, and ultrasonic sensors (Chun et al, 2020). Additionally, robots have found applications in additive manufacturing, enabling the creation of complex architectural forms through 3D printing. Furthermore, robots equipped with AI and machine learning capabilities are programmable to execute a wide range of complex tasks in collaboration with humans.

Advancements in robotics have led to the development of automatic modular designs, where robots function on control software and optimization algorithms to assemble modules within architecture (Broc et al., 2019). This final process of automatic modular design has introduced new interactions between humans and robots in the construction design space. Moreover, advancements in neuro-evolution in robotics have enabled the design and integration of software involving robotics into neural networks (Woods et al., 2019). These prospects show promise as a viable alternative for robotics in neuro-evolutionary design methods, offering greater efficiency, performance, and transferability in shaping the future construction space with robots involved in automating certain processes (Garzon et al., 2020). Studies, including Lehman et al. (2020:198), envision that these robots, 'through novelty search algorithms, can select control software that exhibits behavioural novelty compared to previously encountered behaviours.' They utilize their algorithms to enhance quality concerning a mission-specific objective function and behavioural novelty in relation to previously encountered instances of control software.

2.3 Robotics and Building Construction in the UK

The advancement of robotic and automation technologies holds significant promise for the infrastructure sector in the UK. One prospective outcome is its impact on labour and construction jobs. Projections by Deloitte suggest that these technologies will contribute over 2.5 million jobs to the UK construction industry (Deloitte, 2019). It is important to note that many of these technologies still require human input for operation and collaboration (Pan et al., 2021), dispelling the notion that robotics will lead to widespread unemployment. Evidence from the United States supports this, showing that despite a significant increase in industrial robot usage in the automotive industry between 2010-2015, employment in the sector grew by over 230,000 (Berriman & Hawksworth, 2017). Additionally, reports from PwC demonstrate that robots not only create new job opportunities but also enhance specialization and skills development in handling and maintaining the technology (PwC, 2019). The use of robotic technology in the UK construction industry offers numerous benefits, including increased productivity, enhanced safety measures, and reduced costs. However, it's crucial to acknowledge that challenges remain, such as high initial costs, lack of standardization, and a shortage of skilled workers to operate and maintain the technology.

Despite these hurdles, the overall potential for robotic technology to revolutionize the construction industry in the UK is undeniable.

Further investment in robotics and automation is poised to drive research, innovation, and advancements to enhance their application and utilization in the economy. These technologies are recognized for their role in driving efficiency across various construction sub-sectors, including pre-fabrication, in-situ fabrication, modular construction, and offsite construction. Research from China, Japan, South Korea, and the United States supports this, indicating that robotics can lead to 25-33 percent lower labour costs and improved performance (Sirkin et al., 2015; Keating et al., 2017; Faustie et al., 2018; Delgado et al., 2019).

Moreover, investment in robotic research not only boosts the productive capacity of the UK economy but also fosters innovation and development, enhancing the country's global competitiveness in industry and infrastructure (Flanagan et al., 2019). The industrial sector is a key contributor to a nation's GDP, accounting for a significant portion of global service products. Countries like Japan, China, the United States, and Germany have made substantial strides in this sector on the international stage (Roger et al., 2020). For the UK, robotics and automation offer an opportunity to bridge the gap with highly advanced nations, enabling the export of construction services and the adoption of automated technologies (Gleeds, 2021). Increased exports translate to expanded opportunities and competitive advantages for small and medium construction companies and contractors in the UK. It allows them to augment their financial standing, attract new investments, and tap into new markets overseas.

2.4 Theories of Robotic Adoption

Numerous theories in the literature offer insights into the factors influencing technology adoption, each with its unique perspective and implications for different industries. These theories encompass the Theory of Diffusion of Innovation (DIT), Theory of Task-Technology Fit, Theory of Reasoned Action, Technology Acceptance Model (TAM) and its variations, and the Unified Theory of Acceptance and Use of Technology. The DIT theory delves into the transitional phases of technology acceptance and socialization, shedding light on its uptake (Rogers et al., 1995). Similarly, Hoenig suggests that this theory elucidates the correlation between the rate of technological development and its adoption.

The Theory of Reasoned Action (TRA), advocated by Ajzen & Fishbein, posits that attitudes serve as reliable predictors of technology use, emphasizing the importance of behavioural intentions and underlying beliefs specific to users and the technology in question (Ajzen, 2011). While these theories provide a framework for exploring factors hindering robotic technology uptake, this thesis does not focus on them extensively, as it primarily examines theories related to technology utilization from a psychological perspective, which lies beyond the analytical scope of this research. Instead, this study conducts an in-depth assessment of the Technology Acceptance Model, as it offers a comprehensive exploration of technology acceptance beyond underlying behaviours and intentions, focusing on perceptions that either drive adoption or deter it.

2.4.1 The Technology Acceptance Model (TAM)

The TAM, initially proposed by Davis (1989), stands as a prominent theory elucidating technology adoption factors. Over the past two decades, this theory has undergone several iterations, including TAM I, TAM II, and TAM III, advanced by Venkatesh and colleagues (2000; 2003; 2006). TAM hinges on two core assumptions: perceived ease of use and perceived usefulness, both crucial determinants of adoption likelihood (Braun, 2013). Developed as a predictor of behaviour, the TAM model aims to measure technology adoption determinants, informing stakeholders of implementation impact. Davis (1993) grounded his model on the psychological theory of reasoned action to comprehend human behaviour and influential factors, assessing perceived usefulness in pre-testing phases (Davis, 1989). Research revealed human decision-making mechanisms as pivotal in adoption behaviour, balancing perceived usefulness against potential utilization challenges (Davis, 1993). The model highlights the intricate role of human behaviour and perception in technology adoption (Lu et al., 2019). What is unclear from this theory, however, is the association between the cognitive and affective factors that can serve as intervening variables that can influence objectivity (Araujo & Cassais, 2020). Bandura et al. (2008) termed this phenomenon "outcome judgment," illustrating how individual expectations mediate perception and effort toward implementation. This aligns with the theory of outcome judgment, elucidating how individual expectations drive behaviour toward a given technology.

The TAM model posits that perceived ease of use is pivotal in shaping individuals' beliefs about the effort required to learn and utilize a technology or system (Davis, 1989). Recent research (Wu et al., 2018; Adebowale et al., 2019) underscores the connection between this construct and self-efficacy, highlighting its impact on the predictive adoption of technology.

Accordingly, an individual's perception of a technology's ease of use correlates with the complexity associated with its implementation (Wu et al, 2018). Within the realm of robotic technologies in construction, the perceived ease of integrating such technology into existing processes serves as a critical determinant of stakeholders' willingness to adopt it (Mahajan, 2014). This underscores the contingent nature of technology adoption, with perceived ease of use serving as a pivotal metric (Duray et al., 2011). Recent investigations into this theory have delineated three key stages of the process. Firstly, external factors, such as the design architecture of the technology, shape individuals' perceptions of its ease of use and utility (Robbey & Farrow, 2008). This suggests that technology adoption hinges significantly on design intricacies and perceived ease of use, implying that complex systems are less likely to garner widespread adoption (Robbey & Farrow, 2008).

The second stage involves the affective response to the technology, where the TAM framework considers consumers' emotional orientation as a crucial determinant of their behaviour towards technology (Moore et al., 2017). This perspective suggests that the degree of socialization with the technology influences behavioural outcomes. For instance, a technology perceived as labour-intensive and time-consuming is less likely to be accepted compared to one with a positive affective orientation among users (Azjen, 2011). As Davis (1993) aptly put it, "the higher the affective response, the higher is the likelihood that the behaviour will take place." This underscores the importance of perceived usefulness as a key determinant of technology acceptance, with the acceptance of a technology being contingent upon its perceived benefits to the user. The belief that a particular technology can yield immediate and long-term benefits, improving organizational performance, optimizing time utilization, and enhancing individual performance, can drive the inclination towards its adoption (McDonnell, 2014).

Despite its utility in explaining factors influencing the adoption of robotic technology, the TAM model has faced criticism and identified limitations. One of the primary criticisms is the lack of a clear definition and clarification regarding the concept of perception and ease of use within the theory (Venkatesh et al., 2007). The theory lacks robust parameters to measure or predict what constitutes individual perception and its contextual application. For example, Davis & Morris (2007) highlighted factors such as subjective norms, social dynamics, cultural differences, and compatibility, which are not adequately addressed in the theory's definition of perception. Additionally, TAM incorrectly assumes that increased utilization of a technology inherently leads to better performance (Goodhue, 2007).

Moreover, the theory fails to consider the overall utility of the technology beyond the affective orientation of the user (Moore et al., 2009).

Evidence suggests that the effectiveness of a machine is primarily determined by its design and functionality rather than its aesthetic appeal (Giddy et al., 2017). Venkatesh et al. (2007) argued that the original TAM model had become outdated and needed revision to incorporate the latest innovations in information technology. This led to research efforts aimed at extending the TAM model to accommodate new and emerging technologies, including consumer technologies (Venkatesh et al., 2012; Brown et al., 2017). These extensions shifted the focus of TAM towards assessing technology acceptance based on relevance and output quality, addressing methodological gaps in the original model proposed by Davis (1989). The revised models delved deeper into aspects of system utilization, refining the framework for analysing technology acceptance and usage (Xu et al., 2016). The following section explores these theoretical extensions in detail.

2.4.2 Theoretical Extensions of TAM – TAM 1 and TAM 2

Numerous studies have enhanced the foundational assumptions of the TAM model in elucidating technology acceptance. The extensions – TAM 2 and TAM 3 – offer distinct yet complementary perspectives for examining technology acceptance and its influencing factors. TAM 2 delves into organizational technology acceptance, focusing on how technology performance affects productivity, efficiency, and overall performance (Lu et al., 2009). Building upon the TAM model's limited scope, TAM 2 provides a framework for understanding users' perceptions of technology use (Venkatesh et al., 2010). It emphasizes perceived usefulness over ease of use as the primary indicator of technology adoption and acceptance. Unlike the narrow behavioural approach of traditional TAM, TAM 2 rejects the notion that technology usefulness can solely be inferred from predicted intentions (Moore et al., 2019).

Rather than adhering to the confines of the original model, an extension is proposed to construct a comprehensive framework capable of elucidating and reliably predicting the underlying motivations for technological acceptance within organizational contexts (Venkatesh & Davis, 2000). This extended framework is built upon five key components termed exogenous variables and moderators. These include image, output quality, subjective norm, job relevance, and result demonstrability (Venkatesh & Davis, 2000). Unlike TAM, its emphasis on subjective norm grants individuals' autonomy in shaping their perceptions, serving as a moderator of personal choice and decision-making, rather than solely relying on technology's ease of use (Venkatesh & Davis, 2000). This aspect is posited to directly influence behaviour and aid in predicting actions based on the TRA (Bauren et al., 2016). Furthermore, social groups are highlighted as intervening variables that can moderate behaviour, exemplified by the Fear of Missing Out (FOMO) phenomenon (Bilijisima et al., 2019). However, conflicting studies suggest that subjective norm yields inconsistent results due to varying referent suggestions, thereby challenging its efficacy as a measure of behaviour or intention related to technology utilization (Todd et al., 2009).

In TAM 2, the next construct delves into the DIT theory, which elucidates the link between a technology's perceived usefulness and its association with image and status (Moore et al., 1999). This perspective suggests that companies may be incentivized to embrace new and emerging technologies for the symbolic imagery they project, positioning themselves as industry innovators and demonstrating corporate social responsibility (Gallaher et al., 2017). Thus, adoption is positively correlated with image when it enhances status and confers additional benefits or fosters a positive perception of the technology's utility (Venkatesh et al., 2008). The TAM model's third aspect concerns the technology's job relevance, emphasizing the purported benefits such as increased productivity, profitability, efficiency, and reduced labour costs associated with its adoption (Classons et al., 2007). From this perspective, perceived usefulness moderates the acceptance of the technology; if its usefulness is low, the likelihood of adoption diminishes accordingly (Vessey, 2005). Goodhue (1995) argues that job relevance and the usefulness of innovations are inseparable from the anticipated impact and expected output quality resulting from their adoption.

Output quality and result demonstrability as it relates to TAM 2, refers to the quality of technology in performing assigned tasks as a predictor of its usefulness and adoption (Moore et al, 2011). An increase in output engenders a positive perception of technology and makes a case for its adoption (Ventakesh & Davis, 2008). Result demonstrability refers to the tangible results that are obtainable with the implementation of innovations. This construct argues that the degree to which a technology is embraced is intertwined with the performance it brings (Hackman et al, 2008). The lack of demonstrable evidence pointing to the efficacy of innovations is a higher disincentive to justify its adoption due to the association between work performance and motivation (Braun et al, 2011). However, while this theoretical extension of TAM advanced plausible explanations for the utilisation and rationalisation for adoption of innovations, which improved its analytical posture, it fails to explore the critical determinants of perceived usefulness of the technology within the ambit of its adoption (Murray et al, 2018). The shortcomings of this theory led to further extensions to the TAM 2 model to include broader explanations of the possible determinants of intentions, adoption, and utilisation of technology. The basis for the review was not unconnected to the paucity of literature that provided conceptual clarity on the perceived usefulness and perceived ease of use as it connects with technological adoption (Agarwal et al, 2018).

TAM 3 theoretical extension to the TAM model advanced the argument that the association between behavioural intention is linked to both the ease of use and perceived usefulness associated with the technology (Ventakesh et al, 2008). It essentially maintained the theoretical anchorage of TAM 2 and incorporated critical aspects of the TAM model to establish the antecedents that account for behavioural predictors and decision mechanisms for technological adoption. This included such elements as objective usability, perception of satisfaction from use, and external control, technical ability, and self-efficacy (Ventakesh et al, 2008). It follows the string of analysis that associates the moderating effect of technology adoption to the tripartite factors of know-how, self-efficacy, and output quality as a predictor of adoption or otherwise (Bauer et al, 2011; Rogers et al, 1995; Agarwal et al, 2018; Lu et al, 2018).

2.5 Theories of Robotic Technologies – A Review

The diffusion of innovation (DOI) theory is a widely accepted framework for understanding the adoption of new technology in organizations and society. The theory proposes that the adoption of new technology follows a bell-shaped curve, with early adopters being followed by a larger group of mainstream adopters, and finally by laggards who are resistant to change (Chang et al, 2010). This theory proposes that the adoption of new technology follows a bell-shaped curve, with early adopters being followed by a larger group of mainstream adopters, and finally by laggards who are resistant to change (Lien, 2017). According to the DOI theory, the adoption of new technology can be broken down into five stages. The first is knowledge – in this stage, individuals and organizations first become aware of the new technology and start to gather information about it (Xu et al, 2021; Moore et al, 2022). The second is persuasion – here individuals and organizations evaluate the potential benefits and drawbacks of the new technology and decide whether or not to adopt it. Third is the decision stage, which focuses on how individuals and organizations decide to adopt or not adopt the new technology. The penultimate state is the implementation, and it is concerned with how individuals and organizations put the new technology into practice. Lastly, at the confirmation stage, individuals and organizations assess the results of the technology adoption and continue to use or discontinue it (Lien, 2017).

According to the DOI theory, early adopters are individuals and organizations that are the pioneers in embracing new technology, often driven by the perceived benefits and a willingness to take risks. They play a pivotal role in spreading innovation by providing information and social validation to others. Mainstream adopters, on the other hand, are those who adopt new technology after its success has been demonstrated by early adopters and tend to be more cautious in their decision-making process. Laggards represent individuals and organizations that resist change and only adopt new technology when necessary (Scott et al., 2017). In the context of robotic technology adoption in the construction industry, the DOI theory suggests that early adopters could be companies that proactively invest in new technologies, recognizing their potential benefits for enhancing operations. Mainstream adopters may include companies that prefer to wait until the technology has been proven and widely adopted before integrating it into their practices. Laggards, on the other hand, are likely to be organizations that exhibit resistance to change and only embrace new technology when forced to do so. Leveraging insights from the DOI theory could offer valuable guidance for organizations and policymakers on effectively implementing and promoting the adoption of robotic technology in construction (Cheng et al., 2014).

The innovation ambition theory provides a framework for understanding how organizations and individuals decide to adopt new technologies. According to this theory, the adoption of new technology is driven by the ambition of organizations and individuals to innovate (Wood et al., 2017). Those with a high level of innovation ambition are more inclined to embrace new technologies (Pan et al., 2020). The theory identifies three primary factors that influence innovation ambition: resources, opportunities, and ambition level itself.

Organizations and individuals with ample resources—financial, technical, and human—are more likely to possess a high level of innovation ambition. Moreover, those who perceive abundant opportunities for innovation are also predisposed to higher innovation ambition levels. Importantly, the theory emphasizes that ambition itself drives innovation, irrespective of available resources or perceived opportunities (Xu et al, 2021). In the context of robotic technology adoption within the construction industry, organizations with a strong innovation ambition are more inclined to invest in and adopt new robotic technologies. They perceive opportunities for innovation in their operations and possess the necessary resources to implement such technologies (Inavov et al., 2018). Furthermore, external factors like government policies, industry dynamics, competition, and societal expectations can also influence innovation ambition according to this theory.

The resource-based view (RBV) theory suggests that an organization's adoption of new technology is heavily influenced by its available resources. Specifically, organizations with greater resources are more inclined to adopt new technology due to their capacity to invest in and effectively implement it (Pillai et al., 2020; Simeos et al., 2020). These resources can be categorized into three main groups according to the RBV theory: tangible resources like financial resources, technology, and equipment; intangible resources such as intellectual property, brand reputation, and organizational culture; and organizational capabilities, which represent the collective skills, knowledge, and expertise within an organization. In essence, the RBV theory emphasizes that an organization's resource endowment plays a crucial role in shaping its propensity to adopt new technology, with tangible resources, intangible assets, and organizational capabilities collectively influencing its adoption decisions.

Organizations possessing intangible resources like skilled human capital, a reputable brand, and valuable intellectual property are better positioned to adopt new technology effectively (Fan et al., 2022). Similarly, strong organizational capabilities, including the ability to innovate, implement, and manage new technology, enhance an organization's likelihood of successful adoption (Nam et al., 2021). In the construction sector's adoption of robotic technology, organizations endowed with ample resources such as financial strength, skilled personnel, and robust organizational capabilities are more inclined to embrace robotic solutions. Their capacity to invest in and effectively integrate this technology underscores their competitive advantage. The RBV theory underscores the critical role of resource availability in technology adoption, emphasizing the importance of organizations continuously nurturing these resources to remain competitive and innovative in their respective industries.

The innovation system theory illuminates how the adoption of new technology is shaped by the complex interactions among various stakeholders within the innovation ecosystem, such as governmental bodies, academic institutions, research centers, and businesses (Yang et al., 2019). This framework emphasizes that the adoption of new technology is influenced by the collective dynamics of these stakeholders, alongside the overarching policies, regulations, and institutional frameworks governing the innovation landscape (Roy et al., 2022). Central to this theory are several pivotal components: Actors within the innovation ecosystem, including government agencies, universities, research institutions, and corporations, collectively drive the development and adoption of new technology (Li et al, 2021). Institutions, represented by regulatory frameworks, policies, and legal structures, significantly influence the trajectory of technological innovation and adoption. Networks formed through collaborative relationships and partnerships among actors foster synergies that propel the development and adoption of new technology. Lastly, the outcomes of the innovation system, including novel products, processes, and services, exert a profound impact on both the economy and society at large (Pillai & Ivonov et al., 2021).

The innovation system theory posits that the integration of new robotic technology in the construction sector is intricately tied to the collaborative dynamics among governmental bodies, academic institutions, research entities, and industry players (Moore et al., 2020). This framework underscores the pivotal role of policies, regulations, and institutional frameworks governing the construction domain in steering the innovation process. It emphasizes that technology adoption is moulded by the interplay between stakeholders and regulatory structures within the innovation ecosystem. Hence, stakeholders and policymakers should prioritize fostering an environment conducive to fostering interactions among actors within the innovation system, thereby facilitating the development and adoption of new robotic technology.

Institutional theory provides insight into how organizations embrace novel technologies, shaped by prevalent norms, values, regulations, and industry standards (Tolbert & Darabi, 2019). This theory suggests that organizations tend to adopt technologies aligned with the prevailing norms and values of their respective sectors, alongside regulatory requirements (Gupta et al., 2020). It identifies three primary types of institutions: regulative, normative, and cognitive. Regulative institutions encompass laws and policies dictating technology usage, shaping organizational conduct. Normative institutions comprise shared values and beliefs guiding organizational behaviour. Cognitive institutions encompass knowledge and assumptions driving organizational actions. Additionally, Institutional Theory highlights isomorphic processes, wherein organizations conform to industry practices, influencing technology adoption patterns (Simeos et al., 2022).

In the realm of robotic technology adoption within construction, the institutional theory underscores that the embrace of new robotic advancements is heavily influenced by the prevailing regulatory frameworks, legal mandates, and industry norms governing construction practices (Gupta et al., 2020). It posits that the interplay of policies and regulations, alongside shared values and norms within the construction sector, significantly moulds the trajectory of innovation. According to this theory, organizations exhibit a greater propensity to adopt novel robotic technology when it aligns with the established norms and values prevalent in the construction domain, alongside compliance with regulatory mandates. Moreover, organizations may conform to industry practices, driving adoption decisions within the construction sector. Ultimately, the institutional theory underscores that the adoption of new technology is intricately linked to the prevailing norms, values, regulations, and industry practices within the construction domain.

Social cognitive theory (SCT) offers insight into how the adoption of new technology is shaped by the observation and emulation of others, alongside the perceived benefits and drawbacks of the technology (Alaiad, 2014). According to SCT, individuals and organizations embrace novel technology by observing and replicating the actions of others, while also weighing the potential advantages and disadvantages associated with its adoption (Henschel et al., 2020). This theory posits that learning occurs through observation and imitation of others' behaviour, influenced by factors such as observational learning and self-efficacy. Individuals and organizations assess their capability, or self-efficacy, in executing a task, which in turn influences their inclination towards adopting new technology. Outcome expectations play a pivotal role in the adoption of new technology, as individuals and organizations hold varying expectations about the outcomes associated with adoption, influencing their willingness to embrace it (Marchesi et al., 2020). In the construction industry's adoption of robotic technology, SCT posits that organizations and individuals observe and emulate the practices of others while weighing the potential benefits and costs. When witnessing successful implementation elsewhere in the industry, organizations and individuals are more inclined to adopt robotic technology, provided the perceived benefits outweigh the costs.

2.6 Triaging the Phases of Robotic Adoption

The conceptualization of various phases in the adoption of robotics reflects the complex interplay of factors influencing how countries, organizations, and stakeholders embrace robotic technologies and integrate them into everyday functions within the construction sector. This encompasses not only injury prevention but also how construction stakeholders are increasingly open to adopting and utilizing robotics in conjunction with their health and safety protocols. Moreover, it encapsulates perceptions surrounding robotics usage and adoption. This conceptualization stems from various theories on robotic adoption explored in preceding sections but extends beyond them to elucidate why these phases may indicate a continuum of robotic adoption—a process wherein robots undergo adoption, utilization, and re-evaluation within the construction industry. Consequently, four phases are delineated to elucidate the different stages of robotic adoption: the lag phase, acceleration phase, climax phase, and re-innovation phase. These phases will be discussed in greater detail below.

2.6.1 Lag Phase

The lag phase of robotic adoption encompasses three key aspects. Firstly, it represents the initial stage where the consideration, assessment, and decision-making regarding the integration of robots into construction processes occur. This phase involves learning, deliberation, and determination of the most suitable type and utility of robots, particularly in areas prone to high injury risks or repetitive physical exertion (Mora et al, 2019). Secondly, the lag phase is characterized by a state of potential growth, indicating a low initial uptake of the idea of incorporating robots into construction practices. However, there exists a burgeoning momentum among construction stakeholders to embrace this concept and integrate it into their workflows. Thirdly, the lag phase serves as a quasi-experimental period marked by ideation and research aimed at identifying the most suitable robotics for injury prevention in construction. It represents a pre-seed stage preceding exponential growth and the transition to a more knowledgeable phase of robot adoption. While the lag phase is heavily influenced by various factors such as public perception, stakeholder interests, and regulatory frameworks, it holds immense significance as it often determines whether an organization will proceed with robotic adoption (Callum et al., 2021; Greene et al., 2021). Importantly, the lag phase is not necessarily a fixed stage, as certain factors may prompt organizations to bypass this phase in their journey toward robotic adoption.

However, contrary to some studies (Chu et al., 2018), it is argued that even if organizations bypass this phase, the underlying rationale behind conceptualizing a lag phase model prompts them, and by extension, countries (from a policy perspective), to contemplate the why behind construction robots and the necessity of this innovation. Nevertheless, an organization's positioning within this phase is influenced by a variety of factors, including the cost of adoption, incentives for uptake, the functionality of the robots, and the urgency of need (Wang et al., 2021). There is no universal formula for determining why the lag phase may be prolonged in certain instances. However, research has indicated (Ilaboye et al., 2021; Olabode et al., 2021) that the level of technological advancement plays a significant role, along with the presence of an enabling environment conducive to the use of robotics. Factors such as regulatory policies and government funding also shape the landscape, determining which types of robotics are permitted. Moreover, research efforts play a crucial role in shaping the trajectory of robotic adoption.

2.6.2 Acceleration Phase

The acceleration phase, as its name implies, represents a period of rapid growth or increased adoption of robots (Sica et al., 2019). It is characterized by a substantial surge in the integration of various robotic systems across a wide spectrum of processes previously not deemed suitable for preventing construction-related injuries (Hugh et al., 2019). This phase comprises two pivotal sub-phases. Firstly, there's the phase of acceptance and utilization, where there is widespread industry acceptance by stakeholders, leading to the normalization and socialization of robot usage in the construction lifecycle (Akindoyo et al., 2019). Acceptance here encompasses both integration and systematization. Integration signifies that those processes, once reliant on labour-intensive methods, prone to hazards, and susceptible to health and safety concerns, are now more adaptable to robotic designs and technological innovations such as AI, IoT, machine learning, and the utilization of Big Data (Ilaboye et al., 2022). This phase serves as both a precursor to the boom phase of construction robots and underscores these advancements as a natural and inevitable progression in construction advancement and transformation.

However, scholars such as Rie et al. (2019) and Sinclair et al. (2020) assert that the acceleration phase is predicated on several factors, including the current level of technological utilization, industry preparedness, and the presence of an enabling environment conducive to its implementation. This underscores the intricate ecosystem of various temporal loops involved in driving the acceleration phase forward. Nevertheless, it is important to recognize that acceleration does not necessarily equate to permanence. The risk of these technologies, including robotics, being phased out from the construction process remains present due to technical errors, compatibility issues, high maintenance costs, lack of technical expertise for maintenance, expenses associated with parts replacement, and the level of technical proficiency required for robot operation (Wu et al., 2021; Zubair et al., 2020). According to Ahmad et al. (2021), navigating the acceleration phase necessitates careful consideration of broader factors about safety, data protection, and system vulnerability associated with the rapid adoption of new and emerging digital technologies and robots. On the opposite end of the spectrum, the concept of acceleration extends to automation and semi-autonomy (Moonlight et al., 2020).

Throughout history, novel technologies have consistently reshaped the construction landscape, pushing the boundaries of what is achievable. Their introduction typically garners significant uptake (Cusco et al., 2019). However, as noted by Nineve et al. (2018), uptake, while implying a certain level of acceleration, does not always directly translate into acceleration. In the context of the acceleration phase, the concept of autonomation emerges, signifying the integration of technologies into construction processes to such an extent that robots are increasingly capable of performing tasks either entirely or partially, replacing functions previously carried out by humans through controlled or programmed algorithms (Rutherford et al., 2020). Thus, the notion of acceleration encompasses both a phase and an evolutionary process within construction systems.

The concept of semi-autonomization and collaborative robotic work has seen significant advancements through technologies like the SAM 100 machine, which achieves a remarkable 50% reduction in building costs. Additionally, robots such as Boston Dynamics' Atlas Robots play multifaceted roles, from demolishing built structures to aiding in BIM modelling. Notably, the Hadrian X (FBR) robot, mounted on a truck, boasts the capability of laying more than 1000 bricks per hour, surpassing the speed of 10 human workers.

Furthermore, innovations like EksoWorks, an industrial exoskeleton, mitigate injury risks and physical stress by facilitating manual tasks. nLink, a robotic arm supported by sensor technology, operates on mounted devices like vehicles, enabling tasks such as installing prefabricated structures and pouring concrete. In the realm of advanced construction robotics, TyBot robots streamline rebar tying processes by eightfold, while Built Robotics' site autonomy robots excel in digging, hauling, and grading tasks, leveraging cutting-edge construction technology. Lastly, the Komatsu intelligent construction machinery robot utilizes sensors, controllers, and communication infrastructures to perform a wide range of tasks, including excavation, hauling, bulldozing, and grading, ultimately reducing construction time and enhancing quality.

While autonomation and acceleration share common ground, they operate on distinct levels. Firstly, autonomation remains an ongoing process, characterized by lingering concerns regarding trust and technology. Questions arise regarding the extent to which automation should be permitted and its potential impact on the future of the construction industry, particularly in terms of job displacement and construction quality. These concerns are intricately linked to the policymaking process, which determines the scope of possibilities for automation. Secondly, autonomation is perceived as a dual product of both technology and utilization. While technology showcases what is achievable, contingent upon an organization's capacity to facilitate acceleration and technology utilization, utilization underscores the functionality of these technologies and their integration within the construction domain. This dual perspective emphasizes the interplay between technological capabilities and their practical application in the construction space.

2.6.3 Climax/Peak Phase

The climax phase denotes the pinnacle of robotic adoption, prompting the emergence of newer innovations. Within the climax stage, two key aspects emerge. Firstly, it signifies that the functionality and utility of a specific robotic design or system have been superseded by newer technology (Abidioun et al., 2019). This implies that innovation replaces existing technology, aligning with Silverman's analysis (2017) of the cyclical nature of technology adoption. According to Silverman, every technology undergoes a lifecycle, starting with its introduction to fulfill its intended purpose, followed by adaptation for everyday use and integration into production processes, and ultimately leading to its decline as newer technologies enter the market.

The climax phase of technology is marked by its potential for improvement through updates, whether in the form of hardware or software enhancements (Zoola et al., 2018). However, this may not always be feasible with hardware technologies like robots. The antithesis of this process is a synthesis of new technology ascendancy, its adaptation for use, and eventual decline due to the introduction of newer technologies (Browne et al., 2018). While not all robotic technologies adhere strictly to this model, some endure due to their continued relevance, albeit modified with new technologies while retaining their proprietary core.

Another pivotal aspect of the climax phase in the adoption of robotic technology is its widespread utilization among construction stakeholders globally (Miza et al., 2018). This phenomenon manifests in two distinct applications. Firstly, it implies global dissemination of these technologies due to their proprietary nature, facilitating easy adaptation worldwide. Additionally, the widespread nature may also be localized within specific regions where a common standard for technology utilization has been established. In essence, stakeholders have collectively agreed upon minimum efficiency standards achievable through this technology when tailored for specific purposes. Secondly, this phase signifies the internalization of technology within the construction projects of particular industry sectors (Osondu et al., 2019). This implies that construction workers possess the necessary skills, experience, understanding of health and safety protocols, and proficiency in operating robotic technology, integrating it seamlessly into their work processes. For instance, in parts of the Netherlands, the introduction of 3D bridge design has revolutionized the approach to designing and constructing future bridges (Gustav, 2019).

The climax phase is intricately tied to research and development (R&D), serving as the central hub around which the advancement and utilization of robotics revolve within the context of development (Seede et al., 2018). R&D acts as a pivotal force in charting pathways toward enhanced technology utilization, whether through applied applications or laboratory research. During the climax phase, R&D plays a crucial role in refining the current functionality of robots to ensure that their application aligns with ergonomic standards and meets health and safety regulations. Additionally, R&D aims to enhance the collaboration between robots and human interfaces, thereby optimizing the efficiency of construction processes. Moreover, R&D ensures that innovations are not stagnant, fostering greater permeability into the realm of possibilities with new technologies. In the climax phase, R&D does not operate in isolation but collaborates with existing stakeholders in the construction space to maintain ongoing applications and utilization at the highest possible standards. Simultaneously, R&D efforts are being made to achieve better and more efficient capabilities (Chu et al., 2019).

It is crucial to acknowledge that in the competitive landscape of innovation, reaching the climax stage of any technology doesn't guarantee longevity; rather, it exposes it to the volatility of major innovations that come with the territory (Goldberg et al., 2019). Companies continually seek newer, more adaptive, and increasingly eco-friendly methods to enhance their processes, including the utilization of robotic technologies. In this context, research and development serve dual purposes: enhancing existing innovations and exploring avenues for further improvement through new technologies (Wu et al., 2019). At a macro level, the climax phase also serves as both a means and an end for competitive advantage (Chu et al., 2021). As a means, it becomes a pivotal strategy for large corporations to outmanoeuvre competitors by leveraging proprietary technology and development to mitigate the disruptions caused by unforeseen innovations. In the end, reaching the pinnacle of technological advancement is an expression of the normalcy of new technological changes.

2.7 Categories of Robotic Technologies for Construction

2.7.1 Human-robots/Collaborative robots

Collaborative robots, designed to work alongside humans and capable of autonomous task execution, have evolved significantly since their inception in the 1970s for prefabrication works (Perez et al., 2018; Follini et al., 2021). Originally utilized in the manufacturing sector, these robots are now increasingly employed in construction, equipped with improved dimensions and capabilities to perform a broader range of functions, including collaboration centred on both workers and cognition (Pedro et al., 2020).

The literature identifies various types of collaborative robots, such as autonomous mixed teams, human/robot-directed mixed teams, robot-directed human teams, and human-directed teams (Wolf et al., 2020). Autonomous mixed teams involve collaboration between humans and robots sharing a workspace while performing similar tasks. In contrast, human/robot-directed mixed teams require humans to work alongside robotic partners. Robot-directed collaborations involve robots leading tasks while humans supervise, whereas human-directed teams involve a human worker overseeing robot operations (see figure 1 below). The success of human-robot collaboration hinges on several factors, including robot sustainability, trust, safety considerations, ergonomics, and the complexity of the construction site (Liu et al., 2021). Additionally, factors like building design, task sequence, and robot design can impact the effectiveness of collaborative robots in construction projects (Bryan & Mahya, 2021).

Level of collaboration (LOC)	Coexistence 0	Networking 1	Cooperation 2	Coordination 3	Coalition 4	Collaboration 5
characteristics of collaboration in social settings according to Bruce et al. (2006)		• Aware of organization • Loosely defined roles • Little communication • All decisions are made independently	• Provide information to each other • Somewhat defined roles • Formal communication • All decisions are made independently	• Share information and resources • Defined roles • Frequent communication • Some shared decision making	• Share ideas • Share resources • Frequent and prioritized communication • All members have a vote in decision making	• Members belong to one system • Frequent communication is characterized by mutual trust • Consensus is reached on all decisions
Characteristics of collaboration in technical systems	• No network & connection • Undefined roles (tasks) • No communication • All decisions are made independently • Separate workspaces • Subsequent processing or separate workpieces	• Established network (e. g. telecommunication) • Loosely defined roles (tasks) • Little communication (event-based e. g. warnings) • All decisions are made independently • Separate workspaces • Subsequent processing or separate workpieces	• Provide information to each other • Somewhat defined roles (tasks) • Formal communication (up-on request e. g. specific protocol) • All decisions are made independently • Separate workspaces • Subsequent processing or separate workpieces	• Share information and resources • Defined roles (tasks) • Frequent communication (continuously, >1/h) • Some shared decision making (e. g. central routing) • Shared workspace • Subsequent processing or separate workpieces	• Share tasks • Frequent and prioritized communication (> 1/h, priorities) • All members participate in decision making with differing power of co-decision • Shared workspace • Simultaneous processing of workpiece	• Members belong to one system • Frequent communication is characterized by mutual trust • All members participate in decision making with equal power of co-decision • Shared workspace • Simultaneous processing of workpiece
Example	Excavator and tower crane on a construction site	Crusher and stackers stopping simultaneously at malfuncton	Predictive fueling of an excavator via fuel truck	Mobile logistics robots controled by a central control system	Swarm of tandem rollers with a dominant leader	Tandem lift with two cranes

Figure 1: Human Robot Collaboration Matrix. Source Lie et al (2021)

2.7.2 Off-site Automated Prefabrication Systems

These robots primarily serve to enhance the quality of prefabricated building components and automate the production of building materials at off-site locations. Modelled after their counterparts in the manufacturing sector, they facilitate the creation of customizable and optimized building components. Among these robots are technologies like Building Component Manufacturing (BCM) approaches, which transform materials and low-level components into high-quality building parts. Additionally, 3D printing technologies and additive manufacturing techniques enable efficient material usage, waste reduction, and resource efficiency.

Notable examples of these technologies in action include a 12-meter-long footbridge in Madrid, Spain, printed with micro-fined concrete, and a 3D-printed cyclist bridge in the Netherlands. Furthermore, there have been instances of 3D-printed houses in Dubai, UAE, and the 3D printing of steel by a Dutch robotics company, MX3D, producing a 6-meter layer of bridge from molten steel. These off-site construction robots can incorporate both complex and simple geometries found in traditional structures when building buildings. The use of additive manufacturing techniques in the construction industry has been extensively documented in the literature, outlining the prospects, challenges, and benefits of 3D printing technologies (Kumar et al., 2017; Bolous et al., 2020; Ndlovu et al., 2020). However, one of the main challenges identified is the development of suitable materials and the requisite skills to ensure material and mechanical performance. Additionally, concerns arise regarding the potential impact on employment and the cost-effectiveness of these robots (Boulous et al., 2020).

2.7.3 On-site Automated and Robotic Systems

These construction robots encompass automated and robotic systems employed on construction sites for building, assembling, and creating structures. Initially, single-task construction robots emerged, designed to perform repetitive single tasks akin to those in automotive manufacturing. These robots undertake various activities such as mounting scaffolds, painting walls, assembling bricks, spraying concrete, and serving as mobile robotic arms for monotonous repetitive tasks (Liu et al., 2017). They are primarily stationary, adaptable, and compatible with conventional construction methods. However, one significant criticism of these robots is their challenge in integration with human workers, requiring additional health and safety measures before deployment (Looze et al., 2016). Although newer robots allow for human collaboration on site, their implementation necessitates controlled equipment to execute complex tasks effectively (Eadie et al., 2015).

2.7.4 Exoskeletons

Exoskeletons represent wearable mechanical devices designed to enhance the performance of construction workers (Gao et al., 2017). These technologies assist, augment, and protect workers from physical demands, fatigue, and hazards, improving posture, movement, and overall physical activity (Connor et al., 2019). Although exoskeletons share similarities in functionality and definitive features with exosuits, which are more elastic (Lu et al., 2019), they differ in their applications. The utility of exoskeletons in preventing occupational injuries lies in their functionality and application, including active use with electrical sources during construction (Delgado et al., 2017). Capable of autonomously performing tasks, exoskeletons are particularly useful for activities that are physically straining and increase the risk of permanent injuries and disabilities among workers (Delgado et al., 2017). Consequently, they play a crucial role in reducing the impact of monotonous work and enhancing performance. In recent years, Japanese manufacturers have developed several exoskeletons capable of lifting heavy loads, reducing fatigue, and facilitating the manipulation of materials in awkward positions (Mishuba, 2016) (see figure 2 below for the mechanics of an exoskeleton). Delgado and colleagues (2018) suggest that exoskeletons bridge the gap caused by an aging workforce and help mitigate injuries related to age, especially among older workers engaged in physically demanding tasks on worksites. However, despite their potential benefits, the adoption of exoskeletons faces various challenges, including high costs, energy efficiency, safety concerns, and comfort issues, which act as barriers to their widespread use. Additionally, other concerns include health risks, the risk of falls, technical malfunctions, maintenance costs, durability, usability, and the potential for creating a false sense of safety (which may increase the risk of slips and snags). Moreover, integrating exoskeletons with personal protective equipment (PPE) presents additional challenges (Bogue, 2018; Delgado et al., 2017). The literature distinguishes between two types of exoskeletons: active and passive (Lorenzo et al., 2019; Wu et al., 2020). Active exoskeletons utilize actuators for augmentation, whereas passive exoskeletons rely on manually powered processes to generate user motion, resulting in lower costs compared to active ones (Wu et al., 2020).

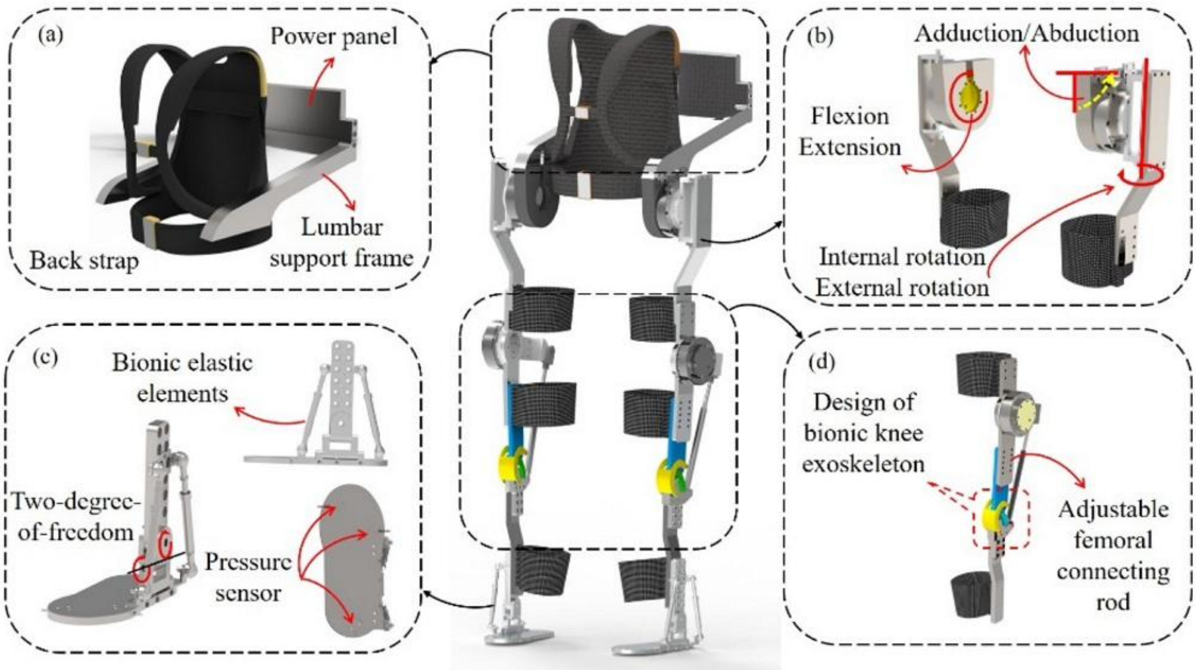

Figure 2: Mechanics of exoskeletons. Source: Wu et al (2020)

Passive exoskeletons offer several benefits beyond their relative affordability. These include reduced joint restriction, decreased body discomfort, lighter weight for ease of carrying, assistance in maintaining correct posture, and prevention of overexertion (Xiang et al., 2021). Additionally, passive exoskeletons can enhance endurance, work efficiency, physiological health, and productivity while mitigating fatigue and overexertion. They operate without power actuators, provide spinal support to prevent musculoskeletal disorders, and contribute to improved worker performance (Weston et al., 2018; Kim et al., 2018; Abdulkarim et al., 2017) (See figure 3 for skeletal support robot). However, passive exoskeletons also carry associated risks, including reduced mobility, potential for long-term harmful working postures, and safety and usability challenges for workers (Spada et al., 2017; Bosch et al., 2016). Despite the highlighted utility of exoskeletons in the literature, there remains a scarcity of studies assessing their deployment and simulation in construction projects in the UK (Kim et al., 2018).

Figure 3: Skeletal support robot. Wu et al (2020)

2.8 Arguments for Robotic Adoption

Several studies have delved into the advantages of employing robotics within the construction sector. Recent advancements in robotics hold the potential to mitigate construction-related injuries in various ways: Automation involves utilizing robots and autonomous machines to diminish the necessity for human workers to undertake perilous tasks, such as heavy lifting, working at elevated heights, or operating in confined spaces (Wu et al., 2021). Similarly, teleoperation entails employing remotely operated robots to execute tasks in hazardous environments, such as nuclear power plants or chemical factories, thereby reducing risks to human workers (Moore et al., 2019). Robotics technology can encompass sensors and safety features capable of detecting and preventing accidents, such as collisions or falls, thus safeguarding workers from injuries. This technology can also enhance precision and accuracy by enabling tasks to be performed with meticulous precision, thereby reducing the likelihood of human errors and resulting in fewer injuries (Gordon et al., 2019). Moreover, robotics technology can monitor and analyse the work environment, identifying potential hazards and offering recommendations for enhancing safety (Pan et al., 2021) (see figure 3 below for a full exoskeleton robot).

Figure 4: Full Exoskeleton on live model. Source: Pan et al (2020)

Recent and ongoing studies (Brock, 2003; Palikhe et al., 2020; Zhang et al., 2020b; Pan et al., 2020; Wang et al., 2021) have highlighted numerous benefits associated with the adoption and utilization of robotics in the construction industry. These benefits include: (i) mitigating hazardous falls from heights, (ii) safeguarding craft workers from repetitive tasks, (iii) preventing injuries to tendons and joints that increase the risk of MSDs, (iv) minimizing lifting and fatigue, (v) mitigating health and safety hazards, (vi) reducing operational costs, enhancing productivity, and minimizing the risk of structural defects, (vii) enabling surveillance functions from elevated altitudes and usage in risky terrains unsafe for humans, and (viii) advanced robots equipped with AI and machine learning capabilities can autonomously act and simulate risks and potential hazards (Zhou et al., 2019).

Recent advancements in robotics have introduced designs with varying degrees of autonomy, enabling them to function in real time without human intervention using pre-programmed algorithms (Walsh et al., 2017). This autonomy allows robots to perform tasks, make decisions, and find solutions independently, without the need for a supervisor or operator. Such capability renders these robots invaluable in dynamic, unstructured, and complex work environments where human agents may face imminent dangers. Moreover, robots can help reduce the risk of sprains, strains, and MSDs associated with repetitive and monotonous tasks. For instance, the Toyota KAIST HUBO-FX1 mobility robot serves as an exemplary case. This robot can be worn as a mobile suit to both enhance power and augment lifting and muscle usage while introducing new capabilities for task performance (Liu and Li, 2018). A South Korean version of this robot has been developed and commercialized to prevent knee impairments and provide support for walking while lifting materials.

New advancements in robotics can potentially reduce construction-related injuries in a few ways: Automation concerns the use of robots and autonomous machines can reduce the need for human workers to perform dangerous tasks, such as heavy lifting, working at heights, or working in confined spaces (Wu et al, 2021). Similarly, teleoperation relates to the use of remotely operated robots that can be used to perform tasks in hazardous environments, such as in nuclear power plants or chemical factories, reducing the risk to human workers (Moore et al, 2019). Robotics technology can include sensors and safety features that can detect and prevent accidents, such as collisions or falls, which can help protect workers from injuries. This can also improve precision and accuracy by allowing the performance of tasks with high precision and accuracy, reducing the risk of human errors, and resulting in fewer injuries (Gordon et al, 2019). In addition, robotics technology can be used to monitor and analyse the work environment, identify potential hazards, and make recommendations for improving safety (Pan et al, 2021).

New advancements in robotics have designs with varying degrees of autonomy and can function in real time without human interference using pre-programmed algorithms. This allows them to perform tasks, make decisions, and find sufficient solutions without a supervisor or operator (Walsh et al, 2017). These make these robots useful in dynamic, unstructured, and complex work environments that would pose imminent dangers to human agents. Furthermore, robots reduce the risk of sprain, strain, and MSDs associated with repetitive and monotonous tasks.

The advancement of robotic and automation technologies has significant prospects in the infrastructure in the UK. The first prospect will have a deterministic effect on the job sector, precisely labour and construction. Projections by Deloitte affirm that these technologies will add more than 2.5 million jobs in the construction industry in the UK (Deloitte, 2019). This is against the backdrop that most of these technologies are not fully autonomous and still require human interface for operations and collaboration (Pan et al, 2021). Evidence from the United States negates the assumption that robotics causes unemployment, as report shows that between 2010-2015, the automotive industry, despite acquiring more than 60,000 industrial robots inventories increased its employment by more than 230,000 (Berriman & Hawksworth, 2017). Furthermore, PwC in a report has demonstrated that robots, contrary to the negative perception associated with these technologies for replacing humans in the workplace, create more opportunities in the handling, maintenance, and use of the technology and specialization of work done (PwC, 2019).

The use of robotic technology in the UK construction industry has the potential to bring significant benefits, including increased productivity, improved safety, and reduced costs. Overall, the use of robotic technology in the UK construction industry has the potential to bring significant benefits and improve the efficiency, safety, and cost-effectiveness of construction projects. However, it is important to note that the adoption of robotic technology in the construction industry still faces some challenges, such as high initial costs, a lack of standardization, and a lack of skilled workers to operate and maintain the technology.

Further investment in robotics and automation is projected to increase research, innovation, and efforts to improve its application and utilization in the economy. This is against the backdrop that is associated with these technologies as driving efficiency in the construction sub-sectors such as pre-fabrication, in-situ fabrication, modular construction, and off-site construction. This is corroborated by research evidence from China, Japan, South Korea, the United States, where robotics has been determined to lead to between 25-33 percent lower labour costs and drive up performance (Sirkin et al, 2015; Keating et al, 2017; Faustie et al, 2018; Delgado et al, 2019). Furthermore, in addition to increasing the productive capacity of the UK economy, investment in robotic research can improve further innovation and development that will boost the UK's global competitiveness in industry and infrastructure (Flanagan et al, 2019). Evidence shows the industrial sector is one of the biggest contributors to a nation's GDP and currently accounts for a fourth of global service products, with many countries, including Japan, China, the United States, and Germany, making a significant leap in the sector internationally (Roger et al, 2020). Robotics and automation present the UK with the opportunity to 'catch up' with the rest of the highly advanced countries in terms of export of its construction services and use of automated technologies (Gleeds, 2021). Increased exports translate to increased opportunities and competitive advantage for small and medium construction companies and contractors in the UK to increase their financial share, attract new investments, and capture new markets overseas.

Table 2: Benefits, safety, and limitations in construction

Type of robotic technology	Uses	Safety benefits and limitations
UAVs or Drones	1. Equipped with cameras, sensors, and GPS systems, and 2. Can be deployed for their aerial ability for surveying, mapping, inspection, and monitoring. 3. Collects data in real time	• Prevents fall risks, reduces hazardous exposures of construction workers to height-related accidents. • Can be limited by weather events. Risk of accidents
Exoskeleton	1. Wearable devices that give strength to workers to carry out repetitive tasks 2. Lifting support 3. Helps in repetitive tasks 4. Gives physical strength and helps reduce fatigue 5. Assist in heavy lifting 6. Improves ergonomics	1. Prevents injuries associated with repetitive tasks 2. Prevent musculoskeletal disorders 3. Improves workers' safety Limitation 1. Expensive to deploy 2. May increase the risk of injuries when not properly customised for a construction worker.
Autonomous construction vehicles	1. These robotic technologies are used for excavation, grading, material transport, and clearing sites	1. Reduces manual labour risks 2. Reduces the risk of human errors and accidents 3. Removes the risk of hazardous vehicle operations Limitations High cost for deployment. May not be amenable to certain construction environments.

Robotic arms	1. Used for performing various mechanical tasks, including welding, bricklaying, concrete pouring, and prefabrication 2. Ensures precision and quality control.	• Reduces repetitive tasks and risks of hazardous exposures Limitation Interoperability concerns.

2.9 Argument Against Robotics: Limitations

Research into the use of robots has been extensive, yet several limitations hinder their effective deployment. Robots pose ergonomic risks due to human-robotic interaction, exposure to electromagnetic fields, and accidents resulting from limited understanding of robotic processes (Bock, 2015). Safety concerns, particularly regarding human-machine collaboration, remain paramount. Olesya (2006) found that inadequate understanding and application of safety requirements for robotic hardware and software heighten safety risks. Guiochet et al. (2017) argue that operating robots demands a level of skill and technical expertise that many construction workers lack, thereby increasing health and safety risks. This complexity in interfacing with robots underscores the importance of considering the social-technical context of robotics use, as highlighted by Pan et al. (2020), to determine their effective adoption and utilization.

The Engineering and Physical Sciences Research Council, in a 2017 report, highlighted several factors crucial for ensuring the safety of robots. These factors encompass the construction site environment, existing health and safety protocols within organizations, technical proficiency, adequacy of building design, managerial support, and developmental adequacy (Warszawski and Navon, 2016). Moreover, studies have delved into the safety implications of robots in industrial construction contexts and their impact on collaborative efforts (Robla-Gomez, 2017). Bogue (2016) examined the use of robots in densely populated environments, shedding light on potential safety hazards. Villian et al. (2018) evaluated intrinsic factors within industrial settings that hinder human-robot collaboration. Additionally, Baratta (2015) emphasized the significance of psychological considerations in workers' interactions with robots throughout the design, construction, development, and implementation phases, as these factors heavily influence workers' perception of safety when working with robots.

Numerous barriers impede the widespread adoption of robots within the construction industry. These barriers encompass a shortage of skilled professionals, risk aversion, limited technology awareness, cultural resistance, high capital costs, and time-consuming setup processes. Studies by Taylor et al. (2010), Bogue (2018), and Okpala et al. (2020) highlight these factors, indicating their role in creating uncertainties surrounding technology adoption and potential applications within construction sites. Furthermore, the integration of smart robotics remains limited in scale, with construction automation strategies still in their infancy in the UK (Berowitz et al., 2019). Currently, there is a dearth of research examining the initial implementation of construction robots and associated engineering processes. Many projections regarding their potential applications rely on speculative assumptions rather than concrete data (Zhang et al., 2020). Pan et al. (2020a) argue that construction robotics remains an emerging field, lacking substantial data from previous applications and scenarios within the construction domain.

2.10 Industry 4.0 Innovations and Construction Health and Safety

Industry 4.0, also known as the fourth industrial revolution, signifies the profound integration of advanced technologies into the construction sector, fundamentally reshaping processes and operations to establish new norms. As outlined by Rojko et al. (2017), Industry 4.0 entails the convergence of Internet of Things (IoT), artificial intelligence (AI), and machine learning within construction, revolutionizing traditional construction methodologies. This paradigm shift mirrors its transformative impact on manufacturing and distribution, prompting experts in technology advancement within the construction sector to align it closely with Construction 4.0. According to Sawhney et al. (2020), Construction 4.0 emerges as a response to the industry's fragmentation across horizontal, vertical, and longitudinal dimensions, advocating for a holistic approach to industry enhancement.

The evolution of Construction 4.0 has led to a closer interconnection among construction projects, resulting in teams working on these projects functioning in isolation, leading to horizontal fragmentation. Construction 4.0, characterized by the integration of technologies such as IoT, Digital Twins, Additive Manufacturing, Cloud Computing, and Cyber-Physical Systems (CPS), aims to automate all phases of construction project lifecycles (Sawhney et al., 2020). Moreover, it entails leveraging information, processes, and knowledge, including human expertise. The Construction 4.0 framework comprises three layers and is driven by the utilization of CPS, enabling seamless communication between virtual and physical devices. This framework prominently features CPS as a foundational element, intricately linking it with the digital ecosystem (Sawhney et al., 2020).

The concept of the digital ecosystem encompasses the reliance on shared digital platforms by a collaborative network of workers to achieve common work goals and objectives (Gartner, 2017). This interconnected ecosystem facilitates various functionalities, including business operations, value creation, and outcomes in the digital realm, facilitated by real-time information sharing over the internet between technological devices and individuals (Moore et al., 2019). However, the central inquiry concerning Industry 4.0 revolves around the potential for modular integration with the construction industry and the extent of its expansion. This expansion is propelled by the pervasive adoption of innovative technological systems that continually incorporate newer interfaces and integrate artificial intelligence into their frameworks (Riebeye et al., 2022). A primary concern is the impact of interconnected technologies on improving construction outcomes while simultaneously reducing the incidence of injuries and fatalities (Mahmood et al., 2022). While there is a case for enhanced data integration through the Internet of Things (Chu et al., 2020), studies have yet to effectively correlate outcomes with expectations (Khan et al., 2017). As Industry 4.0 continues to evolve, significant concerns revolve around privacy, security, data protection, and the ethical boundaries of machine usage and predictive capabilities (Greene et al., 2021). Although ethical considerations may lie beyond the scope of this thesis, they form a critical aspect of exploring the possibilities as technologies advance in functionality, usage, and reach (Sinoa et al., 2021).

One aspect of the debate asserts that there are significant intersections and crossovers between Industry 4.0 and the construction industry, yielding benefits (Iris et al., 2019; Tuban et al., 2021). Advocates of this viewpoint argue that separating technological advancements from the construction domain is illogical. They view Industry 4.0 as an inevitable progression and advocate for the construction industry to embrace innovations to tackle recurring challenges such as injuries and fatalities. In contrast, opposing positions advocate for a more nuanced approach that combines the strengths of Industry 4.0 innovations with those of construction technology (Wang et al., 2019). This approach acknowledges the unique characteristics of the construction sector, emphasizing the need for contextualization and understanding to fully appreciate its intricacies. Innovation is thus perceived not as a one-size-fits-all solution but as an ongoing process that enhances traditional construction methods and offers solutions to existing challenges.

2.11 Shift Shape: AI advancement and Robotics

In recent years, artificial intelligence (AI) has rightfully gained prominence, offering new pathways for problem-solving, reasoning, and mimicking human brain functions. The evolving capabilities of AI are exemplified by innovative technologies such as deep learning, which simulates the neurological system to solve problems using algorithms (Ghaffer et al, 2018). Additionally, AI methods that integrate probabilistic models and machine learning have been deployed in construction sites to assess interdependencies, identify causes of accidents, predict failure occurrences, assess potential hazards, and provide quantitative and qualitative risk data (Afasri et al, 2018). Accenture (2019) highlights the transformative impact of AI, suggesting that it has the potential to enhance labor efficiency by 40% and double annual economic growth rates by 2035. AI methods are also anticipated to serve as the next digital frontier, enabling the transformation of vast amounts of data into actionable knowledge and fostering automation and intelligence across various industries and commerce sectors.

The global construction market is forecasted to expand by 85% to USD 15.5 trillion by 2030, with AI playing a significant role in driving this growth. Projections indicate that AI utilization for productivity enhancement could see an annual increase from 0.8% to 1.4% (Xu et al, 2020). Despite these promising forecasts, the annual productivity of the construction industry worldwide has only experienced an average increase of 1% over the past few decades (Delgado et al, 2021). Studies suggest that the construction sector, amidst industrialization, globalization, and digitization, is poised for a paradigm shift in the next five years, driven by innovative and disruptive technological processes (Greene et al, 2020). Anticipated changes include a transition from a project-based to a product-based approach, increased specialization, enhanced control over value chains and supply chains, industry consolidation, customer-centricity, and heightened investment in technology. These shifts aim to integrate multiple stages of the value chain through digitization, departing from traditional on-site functions (Reed et al, 2019). Future construction processes are envisioned to be more standardized, consolidated, and integrated, with structures and products manufactured off-site. Moreover, the value chain is expected to undergo consolidation, leading to greater internationalization (Tahir et al, 2020). Data and analytics on customer behaviour will inform future designs, shaping a construction ecosystem increasingly reliant on advancements in AI technologies. Digitalization is deemed essential for transitioning toward data-driven decision-making processes and consolidating the value chain (Brown, 2019). AI offers a plethora of applications and benefits for the construction industry, including monitoring, recognizing, analyzing, and projecting safety risks and uncertainties, ultimately enhancing quality and efficiency. Newman et al. (2020) categorize these benefits into three main areas: risk identification, assessment, and prioritization. Despite its transformative potential, AI is still in its infancy in terms of application and adoption in the construction industry.

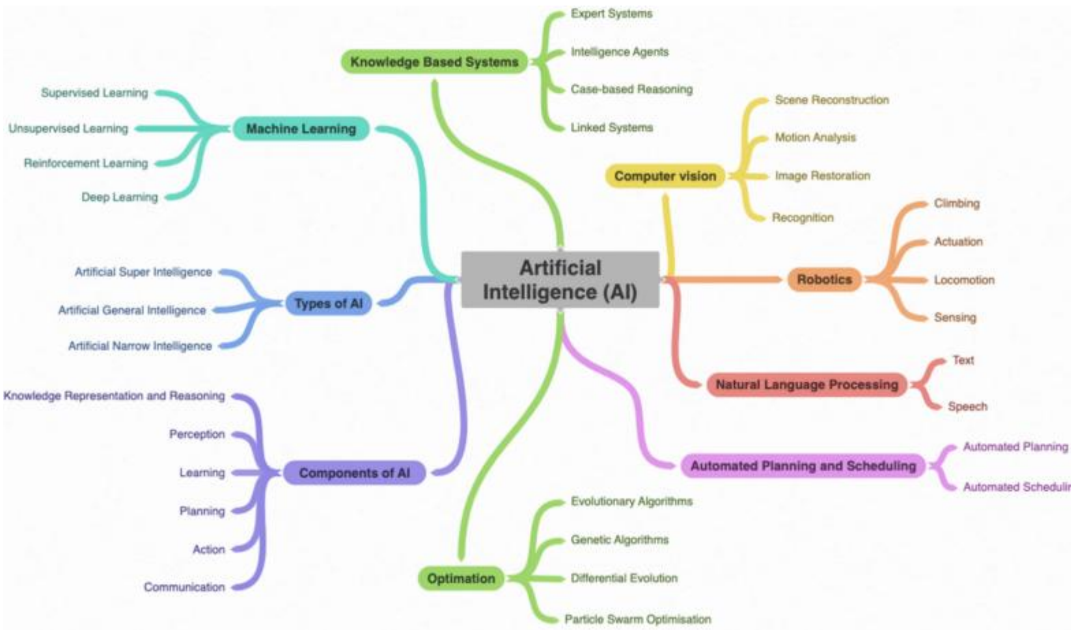

Figure 5: AI in construction. Source: Regona et al (2022)

Companies are poised to increase their investment in AI, signaling forthcoming changes in construction practices (Taylor et al, 2020). This shift entails utilizing AI for decision-making, automation, digitalization, and transforming traditional construction methods. However, the adoption of AI techniques in the construction industry still lags. Numerous reviews in the literature have explored this trend, revealing a growing interest in implementing AI methods across various domains within construction, including structural engineering, building information modeling, automated construction, and manufacturing (Regona et al, 2022; Mehdeb et al, 2022; Okpala et al, 2023). Despite this interest, there remains a limited understanding of the implementation requirements of AI within the industry (Darko et al, 2017). Studies indicate gaps in the uptake of AI technology for prediction and optimization purposes (Yan et al, 2018). For instance, Darko et al (2017) examined the impact of AI in scientific metric analysis and the level of awareness of its utility in construction and found that there is still little comprehensive understanding of the AI techniques and their practical applications. Similarly, Yan et al (2018) analysed literature on AI, data mining, and performance optimization and energy management in the construction industry and found that there are still gaps in the uptake of the technology for prediction and optimization.

While the construction industry is gradually embracing digitalization and automation to enhance productivity, safety, and quality (Moore et al, 2019), AI is emerging as a focal point for businesses recognizing its potential benefits on construction sites (Braun et al, 2020). AI enhances data analysis accuracy, leading to better strategies that benefit all stakeholders involved (Xu et al, 2020). Construction firms must implement AI technologies to boost efficiency, competitiveness, and project outcomes (Wang et al, 2021). AI technologies transform construction practices by increasing efficiency, refining business models, and introducing new services to the market. Given that construction projects are temporary and involve multiple organizations, relying on planning and scheduling models, the industry stands to benefit significantly from incorporating AI technologies (Mato et al, 2016). AI can automate operations and digitalize processes, thereby enhancing productivity, safety, and quality (Wang et al, 2020). This shift towards evidence-based decision-making reduces unforeseen changes that may impact project timelines and costs.

Despite being an emerging topic, AI in construction lacks applied and tacit knowledge. Much of the literature focuses on individual algorithms, limiting the analysis to specific construction stages (Moore et al, 2019). The utilization of AI in the construction sector remains uncertain, largely due to a dearth of research and development (R&D) in AI (Sahir et al, 2020). A significant challenge in assessing the benefits of AI lies in the uncertainty surrounding the returns on substantial investments. This uncertainty is compounded by the persistence of traditional processes in large construction companies that could otherwise be automated, as well as the emulation of similar business models by small subcontractors (Xu et al, 2019). In comparison to other industries, the acceptance of AI within the construction sector is relatively limited. Despite the prevalent discussion of AI in the realm of built environment research, there is a notable scarcity of review studies examining the underlying reasons for the low adoption of AI in construction.

2.12 Modern Methods of Construction or Smart Construction and Robots

Recent studies have delved into the feasibility and effectiveness of integrating robotics into modern construction methods in the UK. Modern methods of construction (MMC) represent a shift towards faster production through mass production, factory assembly, and off-site construction techniques (Sinclair et al., 2020). This approach marks a departure from traditional construction methods characterized by delays, labor intensity, cost issues, and technological limitations (Mira et al., 2019). Originally developed to address post-World War II housing demands, MMC gained traction during the 2005 housing crisis for its ability to expedite construction by utilizing factory-built modules, leading to reduced labor costs, minimized waste, and improved project quality (Arrow et al., 2018). MMC is increasingly recognized as a solution to the UK's housing crisis due to its accelerated construction speed, potential 25% cost reduction, enhanced energy efficiency, and promotion of innovation (UK.GOV, 2021). At an industrial level, MMC techniques include pre-casting concrete foundations, prefabricating floors, employing volumetric construction, and manufacturing panel units in factories (Billar et al., 2019). However, despite its benefits, MMC adoption faces criticism due to perceived quality issues, volatility stemming from regulatory changes, and the demand for a skilled workforce with technical expertise, a shortage exacerbated by Brexit (Millington et al., 2020). Additionally, the economic implications of MMC, such as reliance on imported materials, potentially threatening local manufacturing sectors, pose significant challenges (Rob et al., 2020).

The MMC framework encompasses seven main categories, beginning with pre-manufacturing processes like 3D primary structural systems, where 3D volumes are created off-site and assembled on-site (Agaba et al, 2022). Following this, pre-manufacturing extends to 2D primary structural systems, involving panelised and framing systems assembled off-site for on-site structure construction. Additionally, pre-manufacturing components contribute to the building's structure, while additive manufacturing entails 3D printing components or entire building elements (Miller et al, 2021). Further, non-structural assemblies and sub-assemblies are pre-assembled off-site, consolidating materials and processes that would traditionally occur on-site (Cheng et al, 2021). Moreover, traditional building materials are evolving to improve installation efficiency and safety. Lastly, site labour reduction is achieved through process-led systems aiming to enhance on-site productivity.

2.13 Modern Robotics

The onset of the new century has marked a significant shift in the deployment of technologies that are transforming modern robotics, with a growing emphasis on sustainability, efficiency, and safety in construction (Moore et al., 2021). An important consideration regarding whether advancements in robotics can effectively address the challenges of an evolving industry while preventing associated injuries and reshaping traditional construction practices has been a key aspect of the literature (Xu et al., 2021; Gleeds, 2022).

Projections indicate that the construction robotics market is poised to expand from USD 331.70 million in 2023 to USD 681.80 million by 2028, driven by urbanization, industrialization, and advancements in construction practices (IFR, 2022). In the UK, anticipated government spending is expected to fuel larger residential and construction projects. Although these projects have shorter turnaround times compared to infrastructure and institutional projects, the use of robots in various construction aspects—including 3D printing, autonomous robots, onsite wearables, and modular building designs—has become integral, alongside data analysis and augmented reality, to enhance construction quality.

Modern robots are capable of performing a myriad of tasks in the construction domain, ranging from automating mundane activities like site inspection to enhancing efficiencies in tasks such as tying rebar and undertaking tedious functions using robotic arms and printers. These robots have the potential to enhance safety and generate substantial cost savings, including reductions in legal expenses, sick leave, and labour costs, especially if scaled to significant levels. However, their role is not to replace humans in construction but rather to augment their capabilities and improve the quality of work, even in spaces inaccessible to humans (Oyewale, 2021).

Despite the promising benefits, ethical concerns such as job displacement and data security remain significant. Moreover, as robots increasingly become integral to the construction industry and society at large, several considerations emerge. Firstly, there's the crucial aspect of skill development and training required for workers before integrating robots into construction processes to mitigate the risk of accidents and injuries. Secondly, legislation and regulations play a pivotal role. For example, the European Commission's recent political agreement on new rules aims to ensure the safety of machinery and robots, including those used in construction. The new Machinery Regulation addresses emerging risks and challenges posed by new technologies, covering a wide range of machinery from heavy-duty construction machines to highly digitalized products like robots. It sets forth new safety requirements for autonomous machines and AI systems in machinery, while also aiming to reduce administrative burdens (Sinclair et al, 2022).

2.14 Swarm Robotics

The rise of swarm robotics, where multiple robots collaborate to perform various construction tasks, has become prominent in recent years (Wang & Zhu, 2021; Dongo et al, 2021). Swarm intelligence, pioneered by Beni in 2005, has evolved into a sophisticated discipline focused on generating diverse behaviours (Sahin, 2008). However, it remains prone to errors and can be resource-intensive, depending on the software controlling algorithms that dictate how robots integrate with the designer's intentions (Schranz et al., 2021). In robotic engineering, the online design process occurs concurrently with swarm execution, while offline design precedes swarm deployment for mission execution. Each approach has its implications and considerations, underscoring the nuanced nature of swarm robotics design.

Robotic swarms have surged in prominence over the past decade, representing decentralized systems of relatively simple robots that rely on information to function within workplace settings (Hamann, 2018). These swarms, or multi-robot systems, excel at cooperative task performance (Cheragi et al., 2022), yet they face significant challenges. Firstly, they lack a central control point, both internally and externally, making task coordination difficult, especially for operations requiring human interface. Secondly, their self-organizing nature is constrained by limited local sensing and communication capabilities (Reed et al., 2021). These defining characteristics of robotic swarms underscore their pivotal role in advancing robotic systems. They exhibit remarkable adaptability in dynamic environments (Dorigo et al., 2019) and demonstrate effective interaction among robotic pairs to accomplish diverse tasks, managing large groups of autonomous robots (Rubenstein et al., 2020). Additionally, swarms are scalable systems, resilient to individual robot failures without impeding critical task completion. Despite relatively limited applications in construction, the development of swarm robotics is poised for significant growth in the upcoming decade (Xie et al., 2020; Li et al., 2021). This trajectory suggests a promising future for the widespread implementation of these innovative systems.

Swarm robotics, drawing inspiration from collective animal behaviour, represents an innovative approach to solving complex problems together (Swan et al., 2020; Hou & Lou, 2021). Although literature highlights the potential of swarm algorithms in real-world construction applications, their actual implementation remains relatively rare. Challenges emerge in adapting swarm robotics to construction projects. Firstly, current industrial construction typically operates under centralized systems, conflicting with the decentralized decision-making characteristic of swarm robotics (Cherangi et al., 2022). Secondly, coding local interactions with meaningful context for industrial applicability poses a complex task, given stringent criteria (Olaronke, 2020). Moreover, establishing communication architectures for centralized communication in swarm robotics poses enduring challenges, with large-scale testing considered too risky, despite limited application (Durgas et al., 2019). While simulation has been extensively utilized, its translation to real-world applications remains uncertain. Scholars highlight the transformation of swarm robotics from theory to applied industrial solution as a formidable challenge, necessitating further research and innovation (McCormick et al., 2019).

Examining swarm robotics through the lens of heterogeneity and homogeneity reveals distinct characteristics that differentiate swarm robots from individual ones. Individual robots typically possess processing, communication, and sensing capabilities onboard, enabling them to interact with others and perform tasks semi-autonomously or autonomously (Brambilla et al, 2013). However, in the realm of swarm intelligence, a shift occurs towards a collective behaviour that transcends the capabilities of any single robot. Heterogeneity in swarm robotics refers to the diversity of roles, capabilities, and behaviours among the individual robots within the swarm. Unlike individual robots, which may be designed for specific tasks or functions, swarm robots often exhibit a range of functionalities and behaviours, mirroring the diversity found in natural systems such as insect colonies or bird flocks. This diversity allows swarm robots to adapt to dynamic environments, allocate tasks efficiently, and collaborate effectively towards common goals.

Conversely, homogeneity in swarm robotics pertains to the cohesion and coordination among the individual robots within the swarm. Despite their diverse capabilities, swarm robots exhibit a level of uniformity in their collective behaviour, guided by shared objectives and communication protocols (Soliman et al, 2021). This cohesion enables swarm robots to self-organize, synchronize their actions, and exhibit emergent behaviours that transcend the capabilities of any single robot.

Unlike individual robots, which operate in isolation or under centralized control, swarm robots leverage decentralized decision-making and local interactions to achieve complex tasks collectively. This distributed approach allows swarm robots to adapt to uncertainties, navigate dynamic environments, and collaborate robustly without relying on a single point of failure.

Various types of robots serve distinct purposes in today's construction industry. Primarily, their deployment is rooted in enhancing safety (Wang & Zhu, 2021). Robots play a crucial role in mitigating risks to construction workers by executing tasks that pose potential hazards. For instance, the Hilti semi-autonomous Jaibot system specializes in precision drilling, enhancing drilling efficiency, and conducting installations with minimal human intervention. Capable of handling mechanical, electrical, and plumbing tasks, these machines facilitate modular construction, ultimately streamlining project timelines (Dongo et al., 2021).

Moreover, robots are catalysts for advancements in BIM technology, bolstering the environmental sustainability of buildings by optimizing energy efficiency and conducting energy efficiency analyses through data integration. BIM-based digital twins facilitate future retrofit improvements, ensuring buildings remain sustainable and adaptable as technologies evolve or climate considerations shift. Additionally, robots like Boston Dynamics' Spot are revolutionizing construction progress monitoring through digital twinning, leveraging integrated LIDAR sensors and Simultaneous Localization and Mapping (SLAM) technology. These innovations mark a paradigm shift in how construction projects are managed and monitored, ushering in a new era of efficiency and safety. Specifically, as robots begin to take on roles traditionally performed by humans, concerns about unemployment, job displacement, and the diminishing opportunity for individuals to upskill and receive training become paramount. Moreover, there is a crucial issue regarding the technical expertise required to operate these robots safely. Adherence to strict safety standards is essential to protect workers from potential health and safety risks associated with the use of these machines. Thus, while robotics presents opportunities for improving construction processes, careful consideration of its impact on the workforce and adherence to safety protocols are imperative.

Although robotic swarms offer numerous benefits, they pose significant design challenges. While they operate collectively, achieving desired swarm behaviour is not a direct programming task. Each robot can only respond to local information, necessitating configurations that enable local behaviours to intersect and yield the desired collective outcome (Brambilla, 2013).

2.15 Chapter Summary

This chapter critically analysed relevant conceptual, theoretical, and empirical literature on robotic technology from the prism of understanding the meaning of key terms implicated in this thesis and to understand the theoretical motivations and perceptions underpinning technology adoption and utilisation. This was assessed within the premise of extant theories on the subject, particularly the TAM model and its extension to ascertain the underlying explanations that affect technology adoption. The chapter proceeded to assess the different types of robotic technology, their utility, and applicability in the construction sector.

This chapter undertook an analysis of various types of robotic technologies and their applications in the contemporary construction industry. Specifically, it explored modern robotics, such as swarm robotics, and examined how advancements in robotics technology are reshaping the construction landscape, particularly with the increasing prominence of AI, sensor technology, and automation. A notable finding was the significant lag in the UK's adoption and design-build capabilities compared to other OECD and European countries. Factors influencing this gap were dissected, revealing their deterministic impact on robotics adoption while also highlighting broader considerations. Additionally, the analysis illuminated various types of robotic systems facilitating human-machine collaboration and underscored how advancements in sensor technologies are reshaping the utility of robotics in construction.

This chapter assessed various theoretical frameworks elucidating the stages of robotic adoption, ranging from the Diffusion of Innovation theory to Social Acceptance theory. It appraised the interconnectedness between these theories, revealing how organizations consume and implement innovations, as well as the barriers that may impede their adoption. While these theories are not exhaustive, lacking a universal approach to pinpointing an organization's position or the duration within a specific theoretical framework, the analysis underscores the correlation between the initial stages of robotic adoption and its subsequent trajectory throughout its lifecycle. This analysis informed the delineation of different phases of robotic adoption outlined in the thesis, reflecting the progression from the lag phase to the culmination phase. Through this analysis, it was discerned that the UK construction sector presently operates between the lag phase and the drive to accelerate phase, signifying its initial strides towards enhancing robotics. However, full-scale adoption and implementation of robotics are anticipated to require a considerably longer timeframe.

In the final part of this chapter, the benefits and limitations of robotic technologies were analysed. From the literature review, it is evident that advancements in robotic technology and automation are beneficial for the construction industry in several ways. However, there are apparent limitations that make the uptake of the technology challenging. Having assessed the benefits and the challenges of robotic technology adoption, including the gaps that are affecting its uptake in the sector, a deeper evaluation from the perspective of stakeholders is still undetermined. This is a major gap in the literature, this study seeks to fill. Hence, the need for a data collection process that incorporates the perspective of experts in the UK construction industry to inform the roadmap that can improve its adoption in the sector. This is assessed in greater detail in the next chapter based on the analytical parameters guiding this thesis.

CHAPTER THREE: Robotics and the UK Construction Industry: Situation Scan

3.0 Introduction

A situation analysis of the UK construction industry is undertaken in this chapter to understand the key factors shaping the current trajectory of the industry. The exploratory context is to explore the historical, intrinsic, and extrinsic factors that are shaping the industry and the intersection with technology adoption and use. Furthermore, this chapter examines the construction ecosystem within the gamut of different macro and microenvironments that shape its growth and innovation. This includes the regulatory, stakeholder, political, and broader contexts. This section is important as it provides the analytical bandwidth to properly analyse the issues relating to robotic adoption later in the thesis.

It examines the current level of technology adoption in the UK, the existing legislation and regulations that are affecting its adoption, and the existing health and safety regulations that limit robotic innovation adoption. Another critical aspect of this chapter is the assessment of construction health and safety regulations in the UK and their intersection with construction safety. The main argument buttressed by this chapter is that robotic technology adoption in the UK is not unconnected to the existing regulatory framework, stakeholder perception, economics of adoption, and government policy that act as critical determinants to the level of uptake of emerging and innovative technology. One main aspect of this chapter is the exploration of the barriers to robotic uptake in the UK construction industry.

This argument was assessed within the premise of construction-related injuries and the current level to which innovative technological development in robotics has been used in the sector. To prosecute this argument, this chapter is divided into five parts. The first part assesses robotic technology in the UK – the current level and dynamics. This is followed by an evaluation of the present level of adoption in the UK, including a review of the barriers to uptake. Next is an appraisal of past and current regulations in the UK that are influencing robotic technology adoption in the UK. This is followed by the analysis of the push and pull factors affecting robotics and construction safety in the UK.

3.1 The UK Construction Industry

The UK construction industry comprises distinct sectors, each characterized by unique features that signal a growing inclination towards integrating robotics. These sectors encompass residential, commercial, industrial, infrastructure, energy and utilities, and institutional construction (Baron et al., 2021). Among these, residential construction stands out, claiming the highest market share in the UK construction landscape in 2023. This sector primarily revolves around the development of both single-family and multi-family housing units (Candace et al., 2022).

The UK government has made significant investments in constructing 180,000 affordable homes by 2026, emphasizing the importance of the residential construction sector. Often referred to as housebuilding, it constitutes a substantial portion, contributing 45 percent to the UK's construction output in 2022. Leading players in this sector include Barratt Developments, Taylor Wimpey UK, and Bellway plc. Research has delved into the integration of robots into the construction domain, poised to revolutionize traditional building processes (Calgar et al., 2019). The global robotics market is projected to witness substantial growth, with an anticipated increase of $72 billion by 2022, expected to surpass $283 billion by 2032. Cutting-edge robots, including those adept at bricklaying, are emerging with enhanced efficiency, eco-friendly attributes, and advanced safety features (Lu et al., 2023).

Literature has explored the potential of deploying these robots in residential construction, indicating a forthcoming shift despite the current limited adoption. There are clear indications that these robots will play a significant role in the future, especially for hazardous tasks like repetitive work and real-time construction replication. Moreover, they offer environmental safeguards to prevent worker accidents and injuries, heralding an innovative and sustainable future for the construction industry such as the Ekso Bionics robotic exoskeletons that gets integrated to the body and can be used to distribute the weight of heavy tools, prevent concentrated strains on shoulders and minimise the risk of repetitive tasks (Brown et al, 2021).

The construction industry in the UK encompasses various sectors according to UK.GOV (2023), each with the potential for the integration of construction robotics. Infrastructure construction involves public projects such as railways, bridges, ports, and roadways. Energy and utilities construction encompasses projects related to oil and gas, telecommunications, and renewable energy. Commercial construction focuses on buildings for leisure, hospitality, and similar purposes. Industrial construction involves facilities like factories, power plants, and warehouses. Institutional construction includes educational, healthcare, research, and religious buildings.

In recent years, sustainable construction has gained prominence due to concerns about climate change and the need to reduce emissions throughout a building's lifecycle, from construction to decommissioning. The UK government has set ambitious targets, such as achieving net-zero emissions by 2050, as outlined in the Net Zero Strategy: Build Back Greener (UK.GOV. 2023). This strategy aligns with the definition of sustainable development by the Brundtland Commission, which emphasizes meeting the needs of the present without compromising the ability of future generations to meet their own needs (UNEP, 2022). Human activities, particularly those related to the construction sector, contribute significantly to greenhouse gas emissions, with the building and construction industry responsible for 37% of global emissions. Materials like cement, aluminium, and steel, which have high carbon footprints, contribute to this emission burden.

Achieving net zero in the building and construction industry requires a shift away from unnecessary extraction towards renewable materials, as well as improving the decarbonization of conventional materials used in building (United Nations Environmental Programme, UNEP, 2020). According to the UK Green Building Council, the construction industry contributes more than 20% of total emissions in the UK built environment, including emissions from towns, cities, and infrastructure (UK GBC, 2021). In 2021, the construction industry in the United Kingdom produced over 10 million metric tons of carbon dioxide emissions, making it the second highest emitter after transportation, accounting for approximately 2.4% of total UK carbon dioxide emissions in 2022.

These figures highlight the urgent need to develop and adopt technologies in construction that can reduce greenhouse gas (GHG) emissions and improve energy efficiency. Studies have emphasized the link between technological advancements, robotics, and automation in reducing carbon footprint (Marlene et al, 2020; Greene et al, 2021). By embracing innovative approaches that challenge traditional construction methods, such as using alternative construction vehicles and minimizing waste, the construction industry can achieve better environmental outcomes in terms of carbon savings and promote green construction (Singh et al, 2019).

The intersection between robotics and sustainable construction is an evolving frontier. Despite remarkable progress in innovation with the use of robotics, there remains a gap in how this aligns with the final construction output and green initiatives in the UK. Currently, approximately 25.3% of the UK's electricity is sourced from renewable sources, yet there is a lack of comprehensive data on how much of these savings originate from construction or green new builds (UK.GOV, 2022). Literature explores various ideas, such as renewable energy construction, which investigates the application of automation in constructing renewable energy devices to enhance overall construction efficiency and minimize carbon footprint (Agaba et al, 2020; Oluwole et al, 2023). Another aspect is optimizing energy usage, reducing waste, and conserving energy in the final built construction from commissioning to decommissioning.

The UK government has set specific targets for sustainable building, aiming for all new homes to meet zero-carbon standards by 2025, and for all existing buildings to undergo retrofitting to improve energy efficiency by 2030 (UK.GOV, 2023). While these targets signify progress toward green objectives, there remains a slow uptake of robotic and renewable technology systems to minimize the carbon footprint in everyday construction. For example, constructing wind turbines is considered a hazardous activity, with over 500 onshore-related accidents reported in the UK alone in 2020, including fatalities (HSE, 2021). Drone technology plays a vital role in mitigating the risk of human casualties at such heights and contributes to improved safety standards. Moreover, employing drones for onsite evaluations reduces greenhouse gas emissions from transportation. Drones can reach heights of up to 400 meters, providing superior coverage and enhancing safety and environmental efficiency simultaneously.

Other innovative building options that reduce carbon footprint include 3D printed buildings, which leverage autonomous technology to mitigate risks of injuries, reduce costs and time, and improve GHG emissions levels, fundamentally altering conventional building practices (Marken et al, 2022). Modular construction using 3D technology offers the added benefit of waste reduction, facilitates material conservation, and enhances outcomes. Additionally, integrating electric vehicles on-site minimizes carbon emissions.

Beyond the scope of robotic technology analysis, it is crucial to recognize that robotics is not a standalone solution for achieving net zero in the UK construction industry. Instead, they form part of a broader ecosystem of options available to various stakeholders (Xu et al, 2020). This includes the notion that transitioning to these technologies, whether in the lag phase or acceleration phase, can enhance outcomes in terms of reducing carbon footprint through improved robotic-human collaboration, achieving construction durability, enhancing energy efficiency, indoor air quality, water conservation, and promoting the use of sustainable building materials.

3.2 Push and Pull: Brexit and the Construction Landscape in the UK

In March 2017, the United Kingdom initiated the process of exiting the European Union, commonly known as Brexit. This decision, laden with historical significance due to the UK's deep-rooted ties with the EU across various industries, including construction and its reliance on skilled EU workers, sparked intense debate and scrutiny.

The Brexit agreement, anticipated to span two years of deliberations before implementation, included a provision for the UK to settle an exit bill of approximately £37 billion (Kenton, 2019). Beyond financial matters, the agreement addressed critical geopolitical and economic considerations. One significant outcome of the Brexit agreement was the removal of the hard border between Northern Ireland and the Republic of Ireland, which remained part of the EU. However, EU citizens residing in the UK retained certain rights (Cambridge, 2020), introducing complexities in immigration and residency regulations. Economically, Brexit raised concerns, particularly regarding British exports (Ragnastad, 2020), and the potential disruption to the free flow of goods, services, capital, and people across borders (Moore et al, 2021). Studies indicated potential long-term repercussions on the British economy and its ability to rebound (Dan et al, 2021; Chu et al, 2021), concerns amplified by the global pandemic, which further slowed down the British economy and others worldwide (Descali et al, 2022).

The UK construction industry felt the seismic effects of Brexit, with studies predicting significant repercussions on employment, output, productivity, and the workforce. Furthermore, the risk of volatility heightened due to supply chain disruptions and the sector's struggle to meet diverse infrastructure demands (Dromey et al, 2017; Sandeep et al, 2020). These challenges were compounded by longstanding issues within the UK construction sector, including sluggish adoption of technology, concerns over job losses, and uncertainties regarding investment inflows. There was also apprehension that the UK might struggle to recover from the impact of restricted free movement of goods and people.

The aftermath of Brexit brought about both immediate and enduring impacts on the construction industry. In the short term, particularly between 2016 and 2017, the pound experienced a notable depreciation of 17.6% against the Euro (Dromey et al, 2017). This devaluation posed a significant challenge for construction employers heavily reliant on migrant workers, as the fluctuating pound reduced the attractiveness of employment for non-native workers. Concerns arose regarding the potential loss of experienced workers due to Brexit's effects.

Data from the Office for National Statistics (ONS) underscored the reliance of the construction sector on migrant labour. Before Brexit, the Annual Population Survey indicated an average employment of 2.2 million individuals in the UK construction sector between 2014 and 2016. Of these, 7% were EU27 nationals, with EU8 nationals comprising 49%, EU2 nationals 29%, EU15 nationals 11%, Irish nationals 10%, and the remaining from other EU countries. In comparison, EU27 nationals working in other industries, excluding construction, exhibited a different distribution (Office for National Statistics, 2023).

The share of migrant workers in the construction industry declined from 10.7% in 2020 to 9.8% in 2021, further dropping to 9.3% in 2023 (Office for National Statistics, 2023). Notably, a substantial proportion of these workers were concentrated in London (46.1%), followed by the East of England (15.9%) and South-East England (12.2%). This trend aligns with the significant skills gap identified in the UK Trade Skills Index 2023, highlighting the need for 937,000 new entrants into the construction and trades sector over the past decade, with Scotland alone requiring 31,000 (Construction Industry Training Board, CITB, 2023).

While the UK has moved past Brexit, it will take years to fully recover from its aftermath, particularly regarding labor shortages, skilled labor, and the economic fallout. Despite some progress in addressing acute shortages, the construction sector is still recovering, especially as many experienced construction workers returned to Europe. Although the effects of Brexit may linger, scholars suggest that a full resurgence is achievable through greater automation in robotics and smart technologies (Aghimien et al., 2021).

3.3 Robotic Laboratories in the UK

Several laboratories currently operate in the UK in partnership with universities, playing a pivotal role in advancing innovation and research in robotics development. They aim to expedite the commercialization and industrial application of robotics. One notable example is the National Robotarium, a collaboration between Heriot-Watt University and the University of Edinburgh in the UK. This facility is dedicated to generating innovative solutions using robotics, AI, and automation technologies, with a focus on transitioning these developments from the laboratory to the market (National Robotarium, 2022). Officially inaugurated in September 2022, the centre serves a dual purpose. Firstly, it functions as the national hub for teaching and advancing robotics education for the upcoming generation, facilitating research with a market-oriented approach and equipping graduates with specialized knowledge in data, programming, and robotics development to meet future workforce demands. Secondly, it provides support for accelerating businesses and technology startups, offering laboratory space to nurture ideas that will shape the future of robotics development.

Another notable laboratory is the Lancaster Intelligent and Robotic Autonomous Systems Research Centre (LIRA) at the University of Lancaster. Established in 2018, LIRA aims to promote and facilitate research and expertise in robotics and autonomous systems (LIRA, 2022). It focuses on advancing AI and machine learning research and collaborates with laboratories across Europe to enhance learning and development in robotic systems. For instance, through its European Laboratory for Learning and Intelligent Systems, scholars, particularly research fellows and PhD students, can engage in collaborative learning. This partnership includes a €10 million European AI Centre of Excellence, fostering cross-institutional research and innovation in AI and robotics. ELSA, the European Lighthouse on Secure and Safe AI (ELSA), is a collaborative initiative comprising researchers from 26 leading European research institutions and companies specializing in AI and machine learning. In addition to its primary partners, ELSA collaborates with industry bodies such as the 12M€ Horizon Europe project TAILOR, and is a member of the CLAIRE Network and the ELISE project, a €12M endeavour funded by the EC (ICT-48 call "Towards a vibrant European network of AI excellence centres"). ELSA also collaborates with the European Space Agency's Phi lab to advance frontier knowledge in AI (LIRA, 2022). However, while ELSA's laboratories primarily focus on digital innovations in the AI space and industrial robotics, they do not specifically cater to construction-related robotics. Despite this, some of their frontier robotic applications may have potential crossovers for the construction industry.

The University of Loughborough operates a prominent robotic laboratory in the UK, dedicated to pioneering research aimed at enhancing the integration and collaboration between humans and robots, particularly in tasks involving repetition. This laboratory stands as a key player in robotics research, with a specific focus on applications relevant to the construction industry in the UK (Dave et al, 2021). Research conducted at this facility encompasses various areas, including investigations into precise control and the efficacy of highly non-linear manipulation devices, the exploration of human-robot collaborations (cobots), robotic programming, and the use of multi-modal communication to facilitate efficient human-robot interaction in industrial contexts. Additionally, research efforts have delved into shared planning for robot interactions and teamwork, especially in hazardous or confined environments.

Another significant area of focus aligning with construction robotics is the utilization of robots to mitigate inherent risks, promote human-robot shared spaces, enhance robot resilience, and develop safety-promoting systems through non-deterministic, learning-based approaches. Additionally, research examines the most suitable methods of cobot collaboration for various environments and the expected levels of task complexity (Bishop et al, 2021). Much of the research conducted at this laboratory resonates with the notion of construction robots as a solution for reducing construction injuries in the UK. The research output from this lab has played a pivotal role in ongoing discussions regarding the utility of robotics in the UK (Wang et al, 2019). While significant strides have been made in research output, there remains a considerable distance to cover in terms of translating these innovations into commercialized and industrially scaled construction robot products in the UK. Nevertheless, insights gained from this research shed light on the primary challenges influencing and fostering the adoption of robotics in the UK construction sector.

Apart from Loughborough, another university making significant strides in robotics research is the Bristol Robotics Laboratory, established in partnership with the University of the West of England. Renowned as the largest academic center for interdisciplinary robotics research in the UK (Greene et al, 2021), this laboratory has garnered acclaim for its collaborations with both national and international partners, spanning across Europe and America. Their research endeavours encompass a wide array of specialties, including aerial robotics such as intelligent aircraft and drones, assisted living robots aimed at integrating robotics with mobility services for older and vulnerable adults, and exploration into bioenergy and self-sustainable systems to facilitate the deployment of autonomous robots in remote areas utilizing microbial fuel cell technologies.

Further research areas delve into neuro-robotics, biomimetics, sensor robotics, cobots, self-repair robots, and smart automation, leveraging advancements in robotic engineering systems to emulate human-like decision-making processes in manufacturing settings. Additionally, the laboratory delves into swarm robotics and computational algorithms that dictate how robots function (Moore et al, 2021). While the Bristol Robotics Laboratory serves as a national focal point for robotics research, its primary focus remains academic. Although the implications of its research have significant tangents for industrial applications, a dedicated focus on the construction industry, particularly in the development of construction robots aimed at enhancing worker safety, is notably lacking, despite potential crossover applications in other sectors.

Significantly, numerous universities across the UK, including Oxford, Cambridge, the Royal College of Art, and Imperial College London, are actively engaged in robotic research, each specializing in diverse themes related to industrial robotics and innovative applications (Xu et al, 2021). However, despite their presence, these robotic research centers have faced criticism for their limited impact on the adoption of robotics in the UK. While this shortfall may not solely be attributed to the institutions themselves, it underscores a distinct disparity between research and actionable innovations. Furthermore, many of these research institutions predominantly focus on areas such as human-robot collaboration rather than specializing in construction robots, despite their pivotal significance. This highlights a notable gap in the landscape of robotic research and suggests unexplored avenues for diversification, thereby enhancing the potential for cross-sectoral benefits from robotic innovations.

3.4 Robotic Technology in the UK

Robotic technology holds great promise for driving innovation in the UK construction sector (UKGOV, 2018). As highlighted by UKGOV (2018), advancements in technology are anticipated to deliver more efficient, cost-effective, and agile services while reducing reliance on labour-intensive processes and enhancing project delivery. This sentiment aligns with the findings of the 2017 parliamentary report titled "Automation and Industrial Strategy," which underscored the transformative potential of robotics and automation in enhancing both work and economic landscapes in the UK. The report emphasized the necessity for a cohesive strategy to integrate robotics into the government's Industrial Strategy and address it as a fundamental component across all its grand challenges (Parliament UK, 2017: 2). Published by the Parliamentary Select Committee on Science and Technology, the "UK Automation and Industrial Strategy" report of 2017 examined the ramifications of automation and robotics on the UK's industrial strategy and economy.

While it acknowledged the benefits of automation, such as heightened productivity and efficiency, it also raised concerns regarding potential job displacement and the imperative for workforce adaptation to new skill requirements. To address these challenges, the report proposed a range of measures for government intervention, including increased investment in research and development, financial support for pilot projects, and the establishment of a national centre dedicated to automation and AI. Additionally, it advocated for comprehensive strategies to assist workers impacted by automation, encompassing retraining and upskilling initiatives. Collaboration between government, industry, and academia was emphasized as pivotal to ensuring that UK businesses remain competitive and at the forefront of technological advancements in automation and industrial strategy (Gallagher et al, 2019). The Made Smarter Report highlights that the UK ranks 24th globally for robot density in manufacturing businesses and lags in productivity. However, it also notes that automation and robotics in UK industries could contribute £183.6 billion over the next decade. Data from the International Federation of Robotics (IFR) confirms the UK's significant lag in robotic installations, particularly in the construction sector. Although UK businesses are advancing in industrial applications, especially in the manufacturing of luxury products relying on robotics for mass production (IFR, 2022), the construction industry still falls behind.

In 2016, the House of Commons Science and Technology Committee released a report stressing the significance of robotic technology in the UK. However, despite a more recent UK Innovation and Strategy report outlining the country's plans for robotization and automation, there remains a notable absence of a clear agenda for implementing these strategies within the construction sector (Newman et al, 2021). Moreover, the rate of technological adoption in the UK construction industry lags behind other sectors such as healthcare, security, education, and finance (Newman, 2021). While numerous industries actively seek and implement innovative technologies to enhance productivity, efficiency, and performance, the construction sector has seen insufficient investment aimed at improving outcomes, particularly for workers (Linner et al, 2020).

Debates within policy circles have been largely dominated by the disruptive impact of emerging technologies on jobs, market performance, and economic structures, shaping discussions on the cost-benefit analysis of their adoption and utilization (Bogue et al, 2018). The slow adoption of robotics and automation technologies in the UK has been attributed to various factors. Firstly, an ageing workforce suggests a potential shift of robotic innovation towards social services, healthcare, and other fields rather than construction (Abdulrahman et al, 2019). Secondly, there is a need to align these technologies with the UK's environmental goals for a low-carbon future (Parliament UK, 2020). Thirdly, the commercialization of these technologies and the UK's ability to compete globally in research and innovation within the sector are critical considerations (Quezeda, 2019). Finally, continual government support and policy incentives are essential for fostering innovative developments (Gleeds et al, 2021). Mahbub identified five interrelated factors influencing the uptake of robotic technology in the UK: robot design, the level of automation in the sector, the degree of commercial industrialization, the type of robot and its adaptability to standard requirements, and its usability in construction sites (Mahbub, 2018). Despite the presence of private and joint-venture businesses in the UK producing robotics, such as the Bristol Robotics Laboratory, Small Robot Company, Ocado, and Tharus, along with contributions from universities, the scale of operations remains limited due to challenges in commercialization and market dynamics (Anderson et al, 2021).

While studies have investigated the cost implications, time required for transition from human-operated to robotic systems, and their economic impact (Wang et al, 2020; Zhang et al, 2021), there remains a notable gap in research regarding the current factors influencing the adoption of robotic technology in the UK. This gap persists despite the existing risk exposure of construction workers and limited exploration of the efficacy of exoskeleton robotic technology in preventing construction injuries in the UK.

Thus, further investigation into the factors affecting robotic technology adoption in the UK is crucial. This not only represents an underexplored area in research but also serves as the analytical foundation for understanding its potential role in preventing injuries among construction workers. Such an assessment necessitates considering both internal and external factors hindering the technology's uptake in the construction industry. An examination of the UK government's strategy and policy stance on robotic technology reveals its supportive stance towards investment and growth in the sector. The UK government's strategy and policy position on robotic technology aims to foster the development and adoption of robots and autonomous systems within the country (Mattias et al, 2019). Recognizing the potential benefits of this technology, including enhanced productivity, improved safety, and cost reduction, the government is making efforts to position the UK as a frontrunner in the realm of robotics and autonomous systems.

The government's strategy for robotics and autonomous systems is focused on investing in research and development. The government provides funding for research and development in robotics and autonomous systems to promote innovation and competitiveness in the field. This has been instrumentalized by encouraging and funding collaboration between industry, academia, and government organizations to accelerate the development and deployment of robots and autonomous systems (Delgado et al, 2020). The plan also aims to support the development of the necessary skills for the robotics and autonomous systems industry, including technical skills, entrepreneurial skills, and digital skills. The supporting innovation component of the plan included funding and support for small and medium-sized enterprises to develop new products and services based on robotics and autonomous systems (Boulous et al, 2021).

In addition is the development of standards and regulations for the use of robots and autonomous systems to ensure the safety and security of the technology (Edwards et al, 2019). The UK government has also established the UK-RAS Network, which brings together leading academics, industry experts, and government organizations to promote research and innovation in the field of robotics and autonomous systems. In addition, the government announced its Industrial Strategy in 2017, which includes a focus on "advanced manufacturing and materials" to make the UK a world leader in the development and use of industrial digital technologies, including robotics and autonomous systems (Brown et al, 2019).

This is not unsurprising as the infrastructure sector is a significant contributor to the UK's GDP. This has been demonstrated by the UK government's projected spend of more than £500 billion on high-quality infrastructure projects by 2020–21 alone (Office of Artificial Intelligence UK, 2021). This is more than three times its previous spending in the sector. The UK National Artificial Intelligence Strategy represents its aspirational plan of the UK to build AI into its economic ecosystem to intersect critical sectors, providing services including transport, energy, transport, and waste in addition to improving its global competitiveness (Office of Artificial Intelligence UK, 2021). The strategy represents its national industrial, geo-strategic agenda with AI at the centre stage of the innovation drive and framework. The strategy is a ten-year plan predicated on three pillars. The goal is to make the UK a global superpower in the delivery of AI in the economy and technological transformations (Regona et al, 2022). It essentially sets out a pro-innovation regulatory environment for the UK and the vehicles for its actualisation in the short to long term. The short-term goals are to build cyber-physical infrastructure, invest in AI research and data availability (Kazim et al, 2021).

The medium-term goal is to advance access to AI skills across the sectors in the UK and in the long term, advance and sustain national research and innovation projects and to deepen the utility of AI and emerging technology in the UK and a transition to an AI-enabled economy across all sectors in the UK (HM Treasury, 2022). The entire gamut of this strategy can be summarised in its three pillars. The first one is to invest in long-term needs for achieving an AI ecosystem in the UK. The second pillar is ensuring that AI benefits all sectors and regions in the UK, and the last pillar is enabling AI innovation and an effective governance regime in the UK (Kazim et al, 2021). A critical assessment, while indicative of the UK government's vision to ensure that the UK transitions to an AI-enabled future and to improve its competitiveness, there is no clear roadmap for the adaptation, application, and implementation of this strategy for the infrastructure and construction industry in the UK (Goodson, 2021). Furthermore, while the strategy is indicative that the implementation of the AI strategy will affect all the sectors in the UK, evidence suggests that compared to other sectors, the construction industry has the lowest installation of robotic and automation technology – thus establishing an inherent gap between policy, strategy, and implementation to address sector with critical need.

3.4.1: Robotic Adoption – Comparative Analysis

Recent data from the World Robotics indicates that global robotics adoption has been steadily increasing since 2013. The figures have risen from 1,332 robots per 1,000 units in 2013 to 4,282 per 1,000 units in 2023, with projections suggesting a further 20% increase by 2030 (IFR, 2024). Annual installations have also surged, with more than 545,500 units expected in 2024. Countries in Asia, Europe, and the Americas now hold the largest market share for robotics, accounting for over 51% of global installations. China alone accounts for more than 28% of these installations, particularly within the manufacturing sector (IFR, 2024). The digitization and robotization of industries have become increasingly common, making the incorporation of robotics across all sectors an inevitable trend.

China currently holds the largest stock of robots in the world (IFR, 2024). The robotization of China's manufacturing sector has spread across multiple industries, including construction, and has driven significant acceleration in its local economy. It is projected that this trend will boost growth in these sectors by an additional 5-10% by 2027, with further double-digit growth expected in subsequent years (Chen, 2023; Xu et al., 2023; Wu et al., 2025). Japan follows as the second-largest market for industrial robots. Robotic installations in Japan are expected to reach 46,576 units by 2024, with a projected 20% increase over the next 5-10 years (Yoshida et al., 2022; Sambo et al., 2023). South Korea ranks next, with increasing installations and adoption of robotics, particularly in its manufacturing sector, where the number of units is expected to grow year on year, reaching 31,446 units. The United States ranks fourth globally in terms of robotics adoption (Adenike et al., 2023).

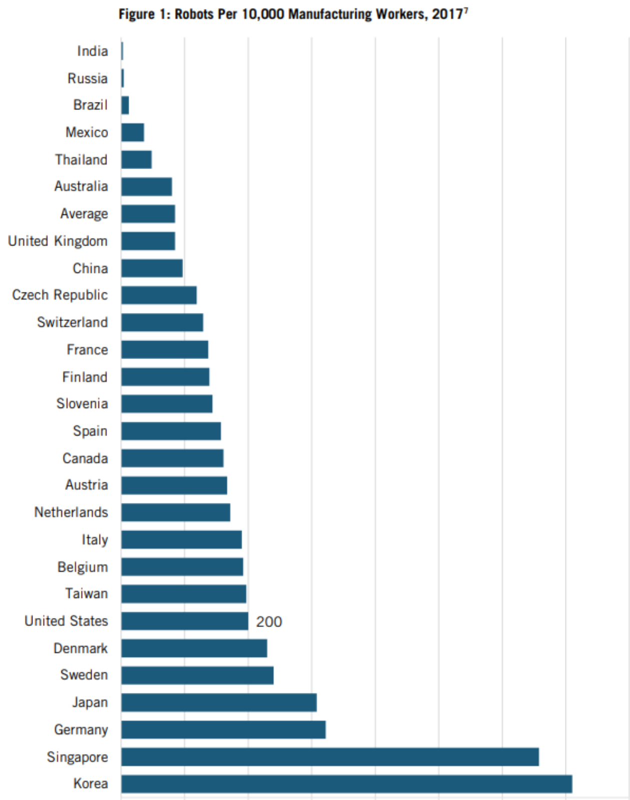

Figure 6: Robotic adoption levels by country - comparative data from 2017 (IFR, 2018)

The figure above highlights how China has made significant progress over the past seven years, surpassing several countries in its adoption and integration of robotics into its manufacturing sector and broader industries. This shift reflects China's innovative strategy and growing competitiveness. According to a 2017 report by the IFR, countries like South Korea, Singapore, and Germany had some of the highest levels of robotic adoption per worker globally (World Robotics, 2018).

For comparative context, before the 2024 figures, data from the IFR in 2015 indicated that South Korea was the leading adopter of industrial robots, particularly in its manufacturing sector. This was followed by Singapore, with Germany ranking third with 322 robots per 10,000 workers, then Japan with 308. The United States ranked seventh, after Sweden and Russia, while India was last among OECD countries, with fewer than 4 robots per 10,000 workers. By 2017, there was a notable shift, with Russia showing remarkable progress, and by 2023, the trend had accelerated even further, reflecting a seismic shift as more countries began to recognize the value of robotics technologies in their industrial sectors. However, by 2024, there has been a notable shift, with India emerging as one of the fastest-growing countries in robotics adoption in Asia, showing a sharp 59% increase in 2023, the highest since 2013 (Bashir et al., 2022). This growth was particularly evident in India's manufacturing and supply sectors, where robotics adoption has seen significant gains (IFR, 2024).

In Europe, the trend has continued upwards, with a 9% increase in total installations across the EU, driven by rising demand for robotics, including in the construction industry. However, the automotive sector saw the most growth in robotics manufacturing, with Spain (5,053 units), Slovakia (2,714 units), and Hungary (1,657 units) accounting for the highest installations. Germany continues to lead in Europe, maintaining its position as one of the top five countries globally, with over 28,000 robots per 10,000 employees in the sector. Italy and France followed, ranking third in Europe. The UK also saw an increase in industrial installations, reaching 3,830 units in 2023, one of the highest increases due to growth in assembly automation (IFR, 2024; Gladenbach et al., 2024).

In the United States, robotics adoption has notably increased, particularly in the automotive manufacturing sector, where it leads as the largest regional market for robotic installations. Since 2018, there has been a steady rise in robotics, particularly in metalworking and machinery, as well as in electrical and electronics industries, which have seen a 10% increase in robotic usage (Berg et al., 2022; Curtis & Wollard, 2023). Canada, too, has seen its highest robotic usage in the automotive industry, with 58% of robotics being deployed in this sector by 2023. Projections indicate an even greater increase in robotics adoption over the next decade, driven in part by the production of electric vehicles (Hutchinson et al., 2021). While Mexico has also experienced growth in robotics usage, its figures do not yet match the levels seen in the United States and Canada (Lam et al., 2023). Globally, robotic installations are expected to surpass 541,000 units, serving as a critical metric for industrialization and technological advancement in countries worldwide (Gall et al., 2023).

In Europe, the UK trails behind countries like Germany, Sweden, Slovenia, Denmark, the Netherlands, Austria, Italy, Belgium, the Czech Republic, France, and Spain in terms of robotics adoption, according to IFR data (2023). Several factors contribute to Germany's high penetration rate of robotics. Studies, such as those by Mahindra et al. (2022), attribute this to the country's high wages and the perception of robotics as an efficient technology that not only boosts productivity but also offers significant labor cost savings across industries (Raza et al., 2020). A similar trend is observed in South Korea, the global leader in robotics adoption, where annual compensation in the most recent year was $45,960, and the payback period for installing a robot was just 15 months, significantly lower than the global average. South Korea's robot density, at 710 robots per 10,000 workers, is 7.35 times higher than the global average (Shuen et al., 2022). This highlights the critical link between payback ratios and annual compensation as key determinants of robotics uptake in countries with high adoption rates.

3.4.2 Robotic adoption in the UK: Comparative Contexts

The robotics industry in the UK has undergone significant changes in recent years, with the government committing to expand and robustly implement AI and innovative strategies to accelerate adoption in the UK (UK Gov, 2023). Data from the International Federation of Robotics (IFR) reveals that the UK has approximately 101 robots per 10,000 employees, which lags behind comparable jurisdictions such as Germany and other European countries that are advancing the use of robotics. Several studies highlight the many benefits of embracing robotic technologies (Chen et al., 2022; Reve et al., 2023; Singh et al., 2024). Projections indicate that both the manufacturing and service sectors in the UK will increase AI adoption, but the growing challenge lies in how adoption intersects with adaptation.

The ongoing debate surrounding robotic technology in the UK centres on the regulatory environment and how existing regulations facilitate the adoption of these technologies. Robotics is increasingly seen as a critical, forward-looking innovation that can revolutionize traditional ecosystems and improve efficiency, reduce labour-intensive approaches, and streamline processes in the UK, both now and in the future. Referring to the Automation and Industrial Strategy (2017), Gleeds et al. (2023) noted that the UK's industrial strategy has been hindered by various factors, including concerns raised by lobbying organizations, labour groups, and others who argue that robotics could replace human workers and lead to job displacement. A report by KPMG (2023) further noted that while robotics adoption has been more widely accepted in manufacturing and services sectors, where its uptake has led to transformative uses and increased appreciation, there remain gaps in its application within agriculture and construction. This is particularly critical, given data from HSE UK (2024) showing that fatalities and injuries in these industries remain the highest in the UK year after year since 2010.

A forensic analysis of the UK's industrial future reveals critical considerations for advancing towards a more robotic and AI-driven landscape. Currently, the manufacturing sector accounts for 10% of the UK's GDP, and this is projected to increase to 15%, contributing an estimated £145 billion to the UK economy (UK Gov, 2023). However, studies by Wang et al. (2023) and Ru et al. (2023) suggest that realizing this growth will require modernizing the manufacturing sector and addressing existing technological gaps in automation and robotics, which the UK currently faces—especially when compared to its peer competitors in the manufacturing sector. The UK significantly lags behind other countries with high automation capabilities, recording the lowest robotics adoption rate in the G7 (Martens et al., 2021). With just 119 robots per 10,000 manufacturing employees, the UK falls short of the 126 robots per 10,000 recommended by the International Federation of Robotics (IFR, 2023). The UK trails behind countries such as Turkey and Mexico in technology adoption, while the Asia subregion hosts more than 75% of the new industrial robots, and the EU maintains steady adoption rates. The UK's robotics growth rate of just 3% is slow, and current projections suggest these rates are insufficient to keep pace with the global trend of accelerating competitiveness.

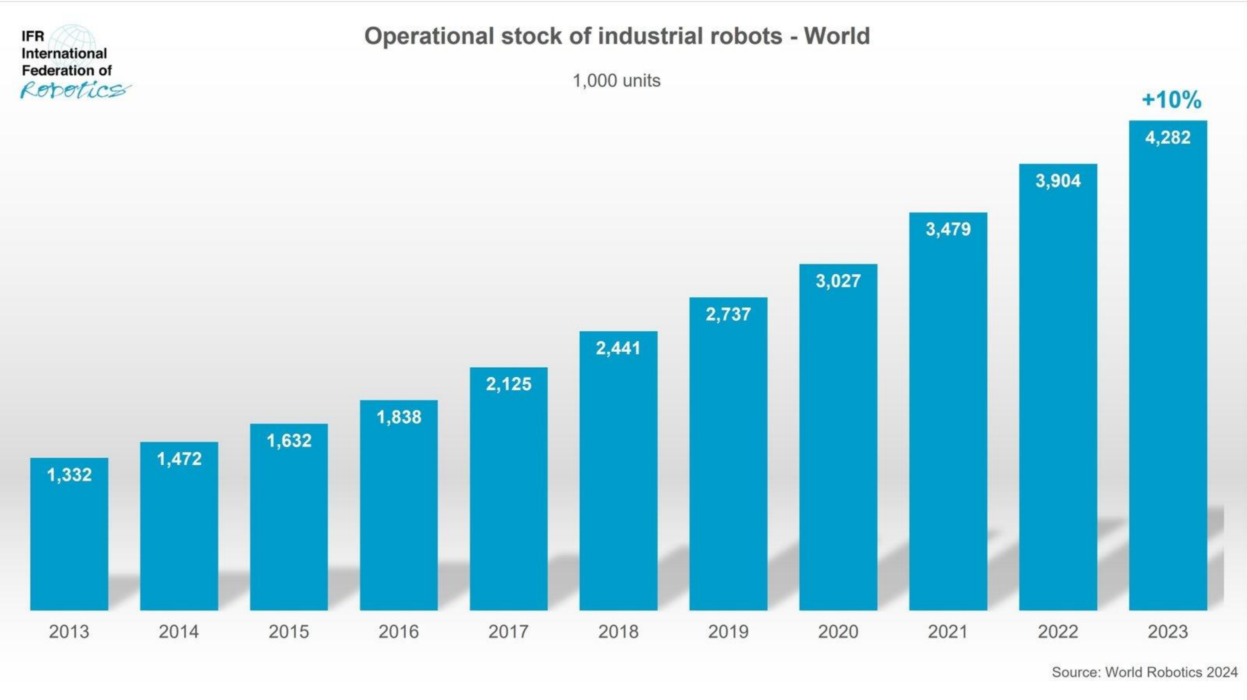

Figure 7: Operational stock of industrial robots in 2024 (IFR, 2025)

Several factors have been attributed to limiting the stakes for robotics adoption in the UK. Projections indicate that the robotics technology market is expected to surpass £280 billion by 2032 (IFR, 2023; Statista, 2024). Many countries, including China, Japan, and South

Korea, are already leading the way in advancing and integrating AI systems and robotics within the manufacturing sector. Goldman Sachs (2023) forecasts that humanoid robots will become increasingly common and ubiquitous across industries and factories worldwide. In the Pacific, Australia is already advancing its national robotics technology with a significant national strategy focused on enabling widespread adoption and integration of AI systems within the industry and its robotics sector (Markys et al., 2023). In contrast, the UK faces more than 72,000 vacancies in critical sectors, particularly in manufacturing and other key industries, where advanced robotics could replace human labor, especially given the aging workforce in many sectors, including construction (Tovan et al., 2022; Seeds et al., 2022). Advanced robotics has the potential to create thousands of high-skilled jobs across integration, maintenance, and manufacturing support roles (Xu et al., 2024).

Table 3: Comparative Overview of Robotic Adoption and Safety Outcomes

Country	Robotic Adoption Rates	Sectoral Usage	Safety Outcome
United Kingdom	Manufacturing: 111 robots per 10,000 employees (IFR, 2023); Construction: 0.3 robots per 10,000 workers	Manufacturing: Moderate adoption in automotive and food sectors; Healthcare: Expanding surgical robotics (e.g., CMR Surgical); Construction: Limited adoption	Healthcare: Improved precision and reduced NHS waiting lists; Construction: Potential injury reduction, but adoption is still low (Finbarr et al., 2022)
Germany	Manufacturing: 429 robots per 10,000 employees (IFR, 2023); Construction: 0.8 robots per 10,000 workers	Manufacturing: High in automotive and electronics; Healthcare: Advanced robotic surgeries; Construction: Moderate uptake	Manufacturing: High automation improves safety; Healthcare: Reduced recovery times (IFR, 2023)
France	Manufacturing: Approximately 200–300 robots per 10,000 employees (IFR, 2023)	Manufacturing: Moderate use; Healthcare: Growing surgical robotics; Construction: Limited data available	Healthcare: Improved surgical outcomes; Construction: Minimal data (IFR, 2023)
United States	Manufacturing: 295 robots per 10,000 employees (IFR,	Manufacturing: Significant, especially in automotive;	Healthcare: Enhanced precision and patient

	2023); Construction: 0.2 robots per 10,000 workers	Healthcare: Widespread surgical robot use (e.g., da Vinci systems); Construction: Low adoption but growing interest	recovery; Construction: Potential for injury reduction but early stage (IFR, 2023)
China	Manufacturing: 470 robots per 10,000 employees (IFR, 2023); Construction: 0.1 robots per 10,000 workers	Manufacturing: Rapid growth via subsidies; Healthcare: Expanding surgical robotics; Construction: Some pilot projects	Manufacturing: Automation addresses safety and labor shortages; Healthcare: Improved surgical precision (Segay et al., 2021; IFR, 2023)

3.4.3 Manufacturing sector and Construction sector: Adoption rates and lessons for the UK

Comparing the above with Europe, it is observable that the UK ranks 23rd globally, and does not make the top ten countries with robotic adoption in Europe. Robotics adoption in Europe has largely underperformed, with Slovenia and the Czech Republic exceeding expectations by 37% and 25%, respectively. However, most EU nations, including Germany (18% below), Spain (25%), Sweden (39%), and Italy (40%), have fallen behind, with Switzerland's adoption rate 84% below expected levels (IFR, 2024).

Conversely, several developing nations outpace expectations. Thailand leads with a 159% higher adoption rate, China follows with a 153% increase, and Mexico exceeds expectations by 16%. Yet, India, Brazil, and Russia lag significantly, with India's adoption 66% below expected, Brazil's 83%, and Russia's 88% (Bashir et al., 2022). The U.S., ranked 16th, is 49% behind expected adoption, with a much slower rate than South Korea, the global leader. This delay is partly due to low capital investment and the lack of a national robotics strategy. While the National Science Foundation's initiative focuses on complementary robots, automation of tasks critical for productivity improvement is largely overlooked (Xu et al., 2024). China, however, has aggressively promoted robotics with massive government subsidies. Its Robotics Industry Development Plan (2016–2020) targets a tenfold increase in robot usage by 2025, with provincial governments like Guangdong and Anhui investing billions. China's pace of adoption is set to surpass South Korea by 2026, reflecting its dominant role in industrial robotics (Chen, 2023).

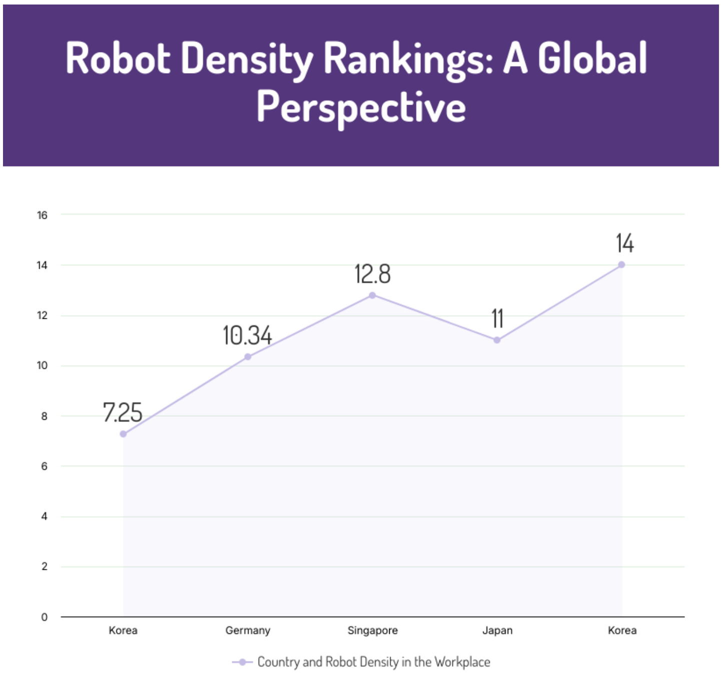

Figure 8: Robotic Density Rankings (IFR, 2023)

Collaboration between government, industry, and academia is seen as a key factor in ensuring that UK businesses remain competitive in the face of rapid technological advancements in automation and industrial strategy (Gallagher et al., 2019). The Made Smarter Report (2024) reveals that the UK ranks 24th globally in robot density within manufacturing, highlighting the country's productivity deficit. However, the report also projects that automation and robotics could generate £183.6 billion in economic contributions over the next decade. According to the International Federation of Robotics (IFR, 2023), the UK remains significantly behind in robotic installations, especially in the construction sector. Although some UK businesses are progressing in industrial robotics, particularly in luxury manufacturing, the construction industry lags considerably (IFR, 2022).

In 2016, the House of Commons Science and Technology Committee recognized the importance of robotics in the UK, yet more recent reports, such as the UK Innovation and Strategy report, have failed to provide a clear agenda for implementing robotics in construction (Newman et al., 2021). The adoption of automation technologies in the UK construction sector has been much slower compared to other industries like healthcare, finance, and education (Newman, 2021). While many sectors actively seek innovative technologies to boost productivity and efficiency, the construction industry has not invested adequately in such advancements, particularly in improving worker outcomes (Linner et al., 2020).

Policy debates have largely centred on the disruptive potential of emerging technologies, focusing on their effects on jobs, economic structures, and market performance, leading to a detailed cost-benefit analysis of their adoption (Bogue et al., 2018). Several factors contribute to the UK's slow uptake of robotics and automation. One significant factor is the aging workforce, which has shifted robotic innovation toward social services and healthcare rather than construction (Abdulrahman et al., 2019). Furthermore, aligning automation with the UK’s environmental goals for a low-carbon future presents another challenge (Parliament UK, 2020). Additionally, the commercialization of these technologies and the UK's competitiveness in global research and innovation remain central concerns (Quezeda, 2019). Lastly, ongoing government support and policy incentives are necessary to accelerate innovation in the sector (Gleeds et al., 2021).

Mahbub (2018) identifies five interrelated factors influencing the adoption of robotic technology in the UK: the design of robots, the level of automation in the sector, the degree of commercial industrialization, the adaptability of robots to construction requirements, and their usability in real-world environments. While there are private companies such as the Bristol Robotics Laboratory, Small Robot Company, Ocado, and Tharus, as well as academic contributions, the scale of operations in the UK remains limited due to obstacles in commercialization and market dynamics (Anderson et al., 2021).

While existing studies have examined the cost implications, transition times, and economic impacts of shifting from human-operated to robotic systems (Wang et al., 2020; Zhang et al., 2021), there is a significant gap in research regarding the specific factors influencing the adoption of robotic technology in the UK. This gap is particularly striking given the high risk exposure faced by construction workers and the limited investigation into the efficacy of exoskeleton robotic technology in preventing construction-related injuries in the UK.

Further exploration into the factors driving robotic adoption in the UK is critical. This under-researched area provides the foundation for understanding how robotics could play a transformative role in improving worker safety. Addressing these factors requires examining both internal and external barriers to adoption in the construction industry. An analysis of the UK government's strategy and policy position on robotics reveals strong support for fostering the growth of robotics and autonomous systems. The government acknowledges the potential benefits of these technologies, including enhanced productivity, improved safety, and cost reduction, and seeks to position the UK as a global leader in this field (Mattias et al., 2019).

The UK government's strategy centres on investing in research and development (R&D) to drive innovation and enhance competitiveness. Funding has been allocated to support collaborations between industry, academia, and government bodies to accelerate the deployment of robotics and autonomous systems (Delgado et al., 2020). The strategy also emphasizes developing essential skills within the robotics and autonomous systems sector, including technical, entrepreneurial, and digital skills. In addition, the plan includes funding for small and medium-sized enterprises (SMEs) to help them create new products and services leveraging these technologies (Boulous et al., 2021).

The UK government has also prioritized the development of standards and regulations to ensure the safe and secure use of robots and autonomous systems (Edwards et al., 2019). The establishment of the UK-RAS Network, which unites leading academics, industry experts, and government bodies, further underscores the government's commitment to advancing robotics and autonomous systems research and innovation. Additionally, the government’s 2017 Industrial Strategy emphasizes "advanced manufacturing and materials," positioning the UK as a global leader in industrial digital technologies, including robotics and autonomous systems (Brown et al., 2019).

This push is particularly relevant given the infrastructure sector's significant contribution to the UK’s GDP. The government’s projected expenditure of over £500 billion on infrastructure projects by 2020–21—three times the previous allocation—illustrates the importance of this sector (Office of Artificial Intelligence UK, 2021). The UK National Artificial Intelligence (AI) Strategy seeks to embed AI within the economy, intersecting critical sectors such as transport, energy, and waste management, while enhancing global competitiveness (Office of Artificial Intelligence UK, 2021). This strategy, a ten-year framework, outlines three pillars: investing in long-term AI infrastructure, expanding access to AI skills, and advancing research and innovation to enable an AI-driven economy (Regona et al., 2022).

Despite these ambitions, a critical assessment reveals a disconnect between the overarching AI strategy and its application within the construction sector. While the strategy aims to foster AI innovation across all UK industries, the construction sector lags in adopting robotic and automation technologies, with installation rates significantly lower than in other sectors. This gap highlights a misalignment between policy, strategic goals, and implementation, particularly in addressing the critical needs of the infrastructure and construction industries (Kazim et al., 2021; Goodson, 2021).

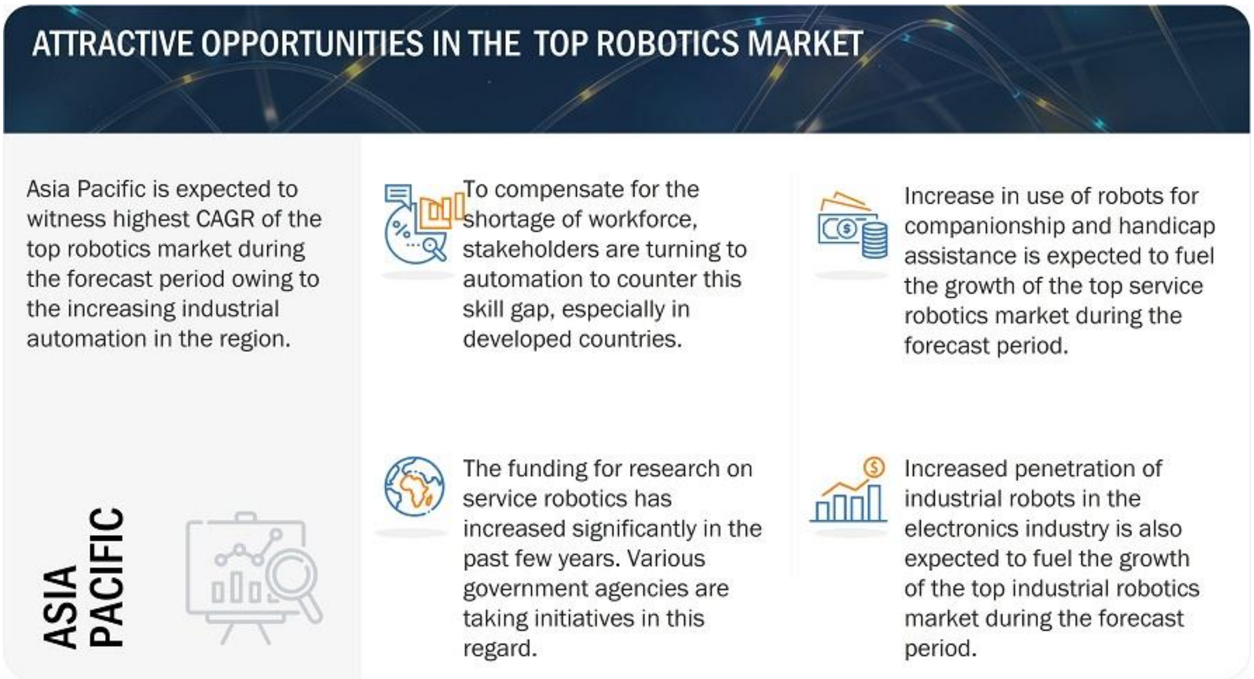

Figure 9: Opportunities for robotics in today's world about CAGR projections (Christopher et al, 2024)

The UK has lagged behind other countries in adopting Automation and Robotics (A&R), particularly in manufacturing. Although some policymakers and industrial organizations have recognized A&R's potential to enhance productivity and reduce operational costs, its integration has been slow, with limited success in implementation (Economics, 2022). UK Research and Innovation (UKRI) and Innovate UK have set a roadmap for A&R integration, focusing on sustainability, efficiency, and competitiveness in manufacturing, but progress remains modest (Innovate UK, 2023).

A&R adoption has made a noticeable impact in improving efficiency, product quality, and safety in the UK's manufacturing sector. Robots are commonly used for tasks like welding and assembly, enhancing precision and minimizing workplace accidents. Furthermore, A&R enables manufacturers to adapt to market fluctuations, boosting global competitiveness. The technology also contributes to sustainability by optimizing resource use and reducing waste. However, concerns about job displacement persist. Evidence suggests that while some jobs may be replaced, overall employment is likely to increase, albeit in different roles. Upskilling and reskilling initiatives are crucial to preparing the workforce for these changes (Economics, 2018).

The adoption of A&R varies across sectors in the UK. The manufacturing sector, particularly in automotive production, has embraced robotics, with a 7% increase in robot installations in 2020 (International Federation of Robotics, 2023). The logistics and warehousing sectors have driven significant adoption due to e-commerce growth, with automated guided vehicles (AGVs) and robotic systems widely used in distribution centers. However, the construction and agriculture sectors face more challenges. The construction sector struggles with complex site environments and regulatory hurdles, while agriculture faces issues related to task diversity and high initial investment costs.

Despite historical underperformance in robot adoption, the UK has significant potential to benefit from A&R. The country is a global leader in robotics research and hosts numerous innovative robotics companies, research centers, and a strong AI ecosystem. By accelerating A&R adoption, the UK could significantly enhance productivity in its manufacturing sector, positioning itself for greater global competitiveness.

3.5 Uptake of Robotics in the UK

A Department for Business, Energy, and Industrial Strategy (BEIS) report paints an optimistic picture of the future of robotics and autonomous systems in the UK. It anticipates a significant economic boost, with robotic technologies projected to contribute £6.4 billion to the UK economy by 2035 (BEIS, 2019). McKinsey's forecast aligns with this outlook, predicting an annual economic value ranging from $1.7 trillion to $4.5 trillion by 2025 from advanced robotics in the UK (McKinsey, 2020). The UK's robotic technology market is poised for substantial growth, with a projected 40% increase over the next decade, driven mainly by advancements in mobile robotics (BEIS, 2020). Oxford Economics predicts that robot installations could potentially add £5 trillion annually to the global economy by 2030 (Oxford Economics, 2020).

However, despite these promising projections, recent data from the International Federation of Robotics reveals a disparity in robotic installations across sectors in the UK. In 2020, only 2,500 industrial robot installations were reported, significantly lower than figures from France, Italy, Germany, the US, and China (IFR, 2020). The construction sector in the UK lags behind other industries like manufacturing, health, and medicine in terms of robotic installations. For instance, while the UK saw a marginal increase in robot sales and installations according to the 2022 report from the International Federation of Robotics, it still falls short compared to other nations (IFR, 2022). Despite the growth potential, there remains room for improvement in the adoption and integration of robotic technologies within the UK's construction sector.

In the latest report from the International Federation of Robotics (IFR), the total number of operational robots in the UK is reported to be 23,000. Despite this figure, the UK's robot market ranks 15th globally, a position significantly lower than that of most industrialized European countries and G7 nations (IFR, 2022). While the automotive industry remains the primary user of robotics in the UK, followed by the food and beverage sector, the construction industry lags behind its European counterparts (Lu et al., 2021). This observation is supported by a recent report from the BEIS, which highlights industries like health and social care, agriculture, energy, food and drink, and logistics as areas witnessing significant robotic application and innovation in the UK (BEIS, 2021). However, BEIS also notes a relatively low adoption rate of robots across industries in the UK, with the country trailing behind peers such as the United States, Germany, and France in leveraging robotics to enhance industry and economic growth. This disparity is further emphasized by findings from the Boston Consulting Group (BCG), which indicate a lack of alignment between ambition and implementation regarding advanced robotics across sectors. BCG's survey reveals that over 90% of companies feel that key enablers, such as a comprehensive vision of future operations, adequate knowledge and training in robotics and automation systems (RAS), and the development of supporting system architecture, are not fully established within their organizations.

The UK Robot and Autonomous Systems report underscores that high-risk sectors in the UK offer promising opportunities for integrating robots into their operational environments (Wolf et al., 2021). Published reports by the UK-RAS Network shed light on the state of the robotics and autonomous systems industry in the UK, highlighting potential benefits such as enhanced productivity, safety improvements, and cost reductions. These reports outline key areas of focus for the UK-RAS Network, including robotics, artificial intelligence, and advanced manufacturing, with a particular emphasis on the construction sector. The network strives to advance robotics and AI technologies to bolster the capabilities of autonomous systems, aiming to enhance efficiency and productivity in manufacturing processes.

Moreover, it advocates for the utilization of robots and autonomous systems in construction, including applications like drones and autonomous vehicles for site inspections and surveying (Pan et al., 2022). In addition to technological development, the UK-RAS Network prioritizes the establishment of standards and regulations to govern the use of robotics and autonomous systems across the UK. This regulatory framework is crucial for ensuring the safety and security of these technologies. While acknowledging the UK's strong position in robotics and autonomous systems, the reports also highlight existing barriers to adoption. Challenges such as cost constraints, skill shortages, and legal and regulatory complexities must be addressed to fully unlock the potential benefits of these technologies.

Several barriers impede the widespread adoption of robots in the UK construction industry. These include a scarcity of skilled professionals, aversion to risk, limited technology awareness, cultural resistance, high initial investment costs, and delays in setup. Studies by Taylor et al. (2010), Bogue (2018), and Okpala et al. (2020) highlight these challenges, indicating their role in fostering uncertainty regarding technology uptake and the development of applications on construction sites. Furthermore, the integration of smart robotics remains at a nascent stage, with construction automation approaches still in their infancy (Berowitz et al., 2019). As for regulation, the UK lacks specific guidelines for the use of robotic technology in construction.

However, the Health and Safety Executive (HSE) has issued guidance outlining how existing health and safety regulations, such as the Construction (Design and Management) Regulations 2015 (CDM 2015) and the Manual Handling Operations Regulations 2002 (MHOR), apply to robotic usage in construction settings. The HSE, tasked with enforcing health and safety regulations, mandates employers to assess and manage risks associated with robot use. Employers must provide comprehensive training on safe robot operation, furnish appropriate equipment, ensure its upkeep, and offer regular health and safety oversight. Compliance with these measures ensures a safe and healthy work environment conducive to robot utilization (HSE, 2020).

Under the CDM 2015, the client, designer, and principal contractor have a legal duty to plan, manage, and coordinate the construction work to ensure that all risks are identified and controlled. This applies to the use of robots as well, which means that the client, designer, and principal contractor must take steps to ensure that the risks associated with the use of robots are identified and controlled (Oswald, 2019). Under the MHOR, employers have a legal duty to assess and manage the risks associated with manual handling activities and to take steps to prevent or control those risks. This applies to the use of robots in manual handling activities as well, which means that employers must assess the risks associated with the use of robots and take steps to prevent or control those risks. Currently, there are no specific regulations in the United Kingdom that govern the use of robotic technology in the construction industry. However, the use of robots in the construction industry is subject to the general health and safety regulations that apply to all workplaces in the UK.

Studies have also determined that the sociotechnical context that which construction robots operate is a key factor affecting their uptake in any system (Pan et al, 2020b). Warszawki and Navon (2016) determined four factors that account for the minimal uptake of construction robots in the construction industry and their uptake in possible future developments: insufficient development, unsuitable building design, inadequate economic basis, and managerial barriers. While similar challenges are obtainable in other sectors, the digital skill gaps in the UK evident in the UK workforce vacancies in the field of AI and construction highlight underlying issues that blight the uptake of its technology (Pan et al, 2021). This is examined in greater detail in the next section.

3.6 Barriers to Robotic Adoption in the UK

Studies in the literature have investigated the barriers to the uptake of robotic technology and emerging technological adoption in the construction industry (Cephas et al, 2018; Matthias et al, 2020; Georgiadou, 2019; Newman et al, 2020). There are several barriers to the adoption of robots in the United Kingdom, including: high costs - the initial investment in purchasing and implementing robots can be high, making it difficult for small and medium-sized businesses to adopt them; lack of knowledge and skills - many companies lack the knowledge and skills required to effectively implement and operate robots, which can be a barrier to adoption; complexity – relating to the installation, programming and integration of robots can be complex and time-consuming, which can be a barrier to adoption and lack of flexibility as many robots are designed for specific tasks, making it difficult to adapt them to different tasks or environments (Georgiadou, 2019, Newman et al, 2020).

Others include fear of job loss, due to the concern that the adoption of robots could lead to job loss and serve as a barrier to its adoption. Legal and regulatory barriers – the lack of clear regulations and standards for the use of robots can make it difficult for companies to adopt; technical limitations - robotics technology still has some limitations in terms of sensors, perception, mobility, and adaptability, which can make it difficult to apply them in certain sectors; data privacy and security - robots may collect and transmit sensitive data, which raises concerns about data privacy and security; return on investment - companies may be unsure of the return on investment they will receive from robots, which can make it difficult to justify the initial investment (Ambode et al, 2018; Wang et al, 2020).

Furthermore, there is also the concern of organizational resistance: Companies may be resistant to change, and may be unwilling to adopt new technologies like robots, despite the potential benefits; organizational resistance – construction companies may be resistant to change and may be unwilling to adopt new technologies like robots, despite the potential benefits and limited infrastructure – construction sites often lack the necessary infrastructure to support the use of robots, such as power supply and internet connectivity. These factors are categorised as the economics of robotic technology, government incentives, usability and adaptability concerns, and the prevailing perception of its acceptance. These factors are examined in greater detail below.

3.6.1 Government Incentive

The role of government incentives as a catalyst for robotic adoption is well-documented in the literature (Reeves, 2021; Olawole, 2022). In Asian countries like Japan and South Korea, where robots have become integral to industrial and manufacturing sectors, government policy incentives play a crucial role in enabling, catalysing, and encouraging further use (Tan et al., 2020). Government policy manifests in various forms, particularly in funding, investing, and providing tax cuts for robotic and automation systems (Whitford, 2020). The UK government holds significant influence in equalizing the competitive landscape for robotic innovation through policy interventions. Government incentives can level the playing field, providing SME companies with equitable access to opportunities for digitization and automation. While efforts are underway, there is room to scale up initiatives, particularly in advancing automation utility and ensuring industry readiness for robotics through favorable policy measures.

The literature emphasizes the pivotal role of government intervention in fostering the adoption of robotic technology, citing it as a major factor influencing its uptake (Georgiadou, 2019; Awwad et al., 2022). The 2019 UK parliamentary report on the future of work and automation underscored government support for a UK Robot and AI Strategy to facilitate industry advancement and manage the shift to automation (UK Parliament, 2019). Moreover, a recent £22 billion Innovation Strategy introduced in the UK aims to promote the development and implementation of seven strategic technologies, including robotics and smart technology, to drive the nation's innovative trajectory (Kwarteng, 2021).

However, despite the rollout of these progressive policies, emerging evidence suggests that technology uptake in the UK continues to encounter obstacles, particularly concerning employment impacts. Calls for a cautious approach to the robotization of sectors like construction, which employ a significant portion of the UK workforce, have been amplified (Gleeds, 2021). For instance, a forecast by PwC estimates that the deployment of over 76,000 drones in the UK by 2030 (currently fewer than 5,000 are operational) for mapping and monitoring motor and railway infrastructure could lead to an estimated 8-12% reduction in the workforce (PwC, 2021). The deployment of SAM, a semiautonomous bricklaying machine, is anticipated to significantly reduce the demand for masons, craftsmen, and labourers in the UK (Awwad et al., 2022). SAM can replace the functions of more than 10 bricklayers, enhancing monitoring and efficiency, albeit requiring human coordination (Wang et al., 2020). These projections align with statements from the UK Chair for BEIS, who acknowledges that the "switch to automation brings challenges for businesses and workers, with fears for livelihoods or disruption to job roles coming to the fore" (Reeves, 2021). Consequently, while government policies provide a direction for the adoption of robotic technologies, the disparity between policy, plans, and implementation, coupled with economic impacts, is impeding the potential uptake of these technologies in the UK.

3.6.2 Perception of Robotic Technology

A 2017 report by the Royal Society UK identified public attitudes toward new and innovative technologies as a limiting factor for their usage in the UK (Royal Society UK, 2017). The report revealed that participants took a pragmatic approach, assessing technology based on perceived intentions, beneficiaries, necessity, appropriateness, human involvement in decision-making, accuracy, and consequences of errors (Royal Society UK, 2017:19). Additionally, the report highlighted three other factors impeding robotic technology uptake in the UK. Firstly, the susceptibility of these technologies to experience boom and bust cycles due to new promises that may fade over time. This aligns with the technological acceptance model, which emphasizes perception and ease of use as key determinants of technology adoption (Braun et al., 2019). However, contrary studies suggest that many technological innovations endure beyond their initial use (Olsen, 2018).

Although recent surveys indicate shifts in public sentiment, underlying concerns persist. A 2023 report by the Department for Science, Innovation, and Technology UK, part of the Center for Data Ethics and Innovation (CDEI), Public Attitude to Data and AI tracker survey, demonstrates an evolving public perception regarding the impact of data-driven technology, including AI. People show greater comfort with these technologies in specific contexts, such as improving health outcomes, IT systems, and education (DSIT cited in UK GOV, 2023). Furthermore, another report (Shawn et al., 2022) identified three additional factors hindering the uptake of robotic technology in the UK. Firstly, there's the susceptibility of these technologies to experience boom-and-bust cycles due to new promises that may dwindle over time. This aligns with the technological acceptance model, which emphasizes perception and ease of use as key determinants of technology adoption (Braun et al., 2019). However, contrary studies suggest that many technological innovations endure beyond their initial use (Olsen, 2018).

Secondly, Marks et al. (2022) highlighted the private sector's leading role in advancing these technologies in the past decade, raising questions about the diminished role of the UK government in technological innovation compared to the 1950s (Dristas & Soe, 2020). Perceptions of a lack of strong government policy incentives to drive the UK's automation and robotic technological advancement in the coming years impede the wide-scale adoption of new technologies (Gleeds et al., 2020). Thirdly, there's concern about the shortage of laboratories and facilities to support robotic innovation and automation research in the UK (PwC, 2021), stifling opportunities for new and emerging innovations compared to countries like China and Japan, which are leading in the trial and implementation of robotic technologies (Miazo et al., 2018).

Related to this is social resistance to robotics. Social resistance to robots in construction can arise from various factors, including perceptions of job threat and safety risks. As highlighted by Wall (2019), the perception of robots as job threats can evoke resistance to their deployment, as individuals fear potential job displacement. Moreover, concerns about the safety implications of robotic involvement may further fuel social resistance. Trust issues also play a pivotal role, as people may hesitate to trust robots in construction settings, impeding technology adoption (McKendish et al, 2022). Additionally, a lack of understanding regarding the capabilities and limitations of robots can hinder deployment efforts, as companies struggle to address misconceptions and educate stakeholders.

Furthermore, generalized fear of technology among workers can exacerbate resistance, making it challenging for companies to implement robotic solutions in construction projects. The perception of robots as a threat to traditional ways of life adds another layer of complexity, compounding resistance to technology adoption. Moreover, resistance to change within organizational cultures can pose significant barriers to the deployment of robots in construction, hindering progress in integrating these technologies into industry practices. Addressing these multifaceted concerns is crucial for overcoming social resistance and fostering acceptance of robotic technologies in construction.

3.6.3 Upfront cost of Robotics

The cost implications of adopting robotic technologies pose a significant barrier to their uptake in the UK. Initial investments in these technologies prompt construction stakeholders to carefully evaluate cost-benefit considerations and return-on-investment before committing to their implementation on construction sites (McMannon et al., 2019). Market demand, client perceptions, and the financial impact of robotization on building costs and site design are key economic factors influencing decisions around robotic technology adoption in construction projects (Buscher et al., 2019). The cost-benefit analysis of adopting robotic technology weighs financial gains against injuries prevented, implementation costs, and the availability of technical expertise to operate these systems (Callum et al., 2018). The return on investment (ROI) associated with robotic adoption hinges on whether these technologies deliver promised efficiency improvements and productivity gains for firms (Delgardo et al., 2017; Braun et al., 2018). Furthermore, working collaboratively with machines on construction sites introduces surface hazards and other safety concerns. While literature highlights potential risks associated with robotic technologies, there is a lack of conclusive studies establishing a direct correlation between robotic technologies and increased incidence of construction-related injuries and fatalities (Wang et al., 2021).

The development and deployment of robots in industries like construction often entail substantial costs, rendering them unfeasible for certain companies or sectors, as highlighted by Sukker et al. (2019). The initial investment outlay, encompassing the purchase, development, and deployment of robotic systems, can be exorbitant, posing a barrier to adoption for many entities, as noted by Xu et al. (2020). Furthermore, the ongoing maintenance and repair requirements of robots in construction, which surpass those of human workers, contribute significantly to the overall cost burden. Additionally, establishing the requisite infrastructure to support robot operations, such as charging stations, incurs substantial expenses. Moreover, robots in construction typically yield limited returns on investment, often being utilized for one-time tasks and subsequently decommissioned, as elucidated by Callum et al. (2018). Additionally, their finite lifespan necessitates replacement, further augmenting costs. Scaling up the deployment of robots across multiple sites or projects also entails considerable expenses, as underscored by Greene et al. (2018). These cost-related challenges underscore the need for careful consideration of financial implications when contemplating the integration of robotic technologies in construction processes.

The integration cost of robots into existing systems and technologies presents a significant financial hurdle. This is compounded by compatibility challenges, as robots must seamlessly interact with various systems and construction management software, such as sensors, cameras, and drones, as highlighted by Cheng et al. (2019). Difficulties arise when these systems employ disparate communication protocols or lack compatibility, hindering smooth integration. Furthermore, robots generate vast amounts of data, posing challenges in data management and integration with existing systems. Additionally, integrating robots into established workflows in construction settings can prove arduous if workflows are not initially designed to accommodate robotic involvement, as noted by Xu et al. (2018). Furthermore, facilitating human-robot collaboration necessitates meticulous system design to ensure seamless cooperation with human workers, as emphasized by Wang et al. (2020). These challenges underscore the importance of addressing compatibility and workflow considerations to facilitate effective integration of robotic technologies in construction processes.

3.6.4 Lack of Standard

The limited uptake of certain robotic technologies in the UK, such as exoskeletons in construction and manufacturing, can be attributed to the absence of standardized development, certification, and established protective methods similar to personal protective equipment (PPE) that ensure their safety in industrial applications (Spada et al., 2017). The lack of standards has been identified as a significant hindrance to their adoption (Kim et al., 2018), a concern echoed by the ASTM International F48 Consensus Standards

Committee for Exoskeletons, which acknowledges the absence of product standards and certification as impacting their potential use in construction industries worldwide, including the UK (Schwab et al., 2019; Anderson et al., 2021). Studies by Kim et al. (2018), Weston et al. (2018), and Abdulkarim & Nussbaum (2019) reinforce the growing interest in utilizing exoskeletons and other technologies to reduce repetitive tasks and injuries in the construction industry. This interest can drive innovative interventions to enhance their applicability and effectiveness.

The absence of standardization in robotics presents a significant challenge for companies seeking suitable technology solutions. Xu et al. (2019) elucidate how this lack of standardization hampers the selection process, complicating companies' efforts to identify the most appropriate technology for their specific requirements. Moreover, the deficiency in interoperability across various types of robots and construction systems further exacerbates integration challenges, impeding seamless incorporation into existing workflows.

Another critical aspect of this issue is the absence of standardized data formats among different robotic systems in construction, hindering data sharing and collaboration efforts among companies. This deficiency not only limits information exchange but also inhibits efficient cooperation between stakeholders. Additionally, the lack of established standards for human-robot interaction in construction poses safety and efficiency concerns for workers (Greene et al, 2021). Without clear guidelines, workers may struggle to interact safely and effectively with robotic counterparts, compromising overall productivity and safety on construction sites. Furthermore, the absence of certifications specifically tailored for robots in construction complicates matters for companies striving to demonstrate compliance with industry standards. Marteens et al. (2020) emphasize the challenges associated with proving the adherence of robotic systems to regulatory requirements, adding another layer of complexity to technology adoption in the construction sector.

3.6.5 Usability and Adaptability

Research has consistently highlighted the time lag between the introduction of new technology and its full integration into the workplace, along with the need for existing staff to acquire new skills to effectively utilize such innovations (Aderigbigbe et al., 2019; Nnana et al., 2019). This learning curve, both in terms of duration and technical complexity, significantly influences perceptions of technology adoption and ultimately affects motivation for its implementation (Braun et al., 2011). Usability concerns also play a pivotal role in the uptake of new technologies. For example, Raila et al. (2019) identified compatibility issues between exoskeletons and other personal protective devices, like fall-arrest harnesses, limiting their adoption. Additionally, the weight of exoskeletons relative to body type and existing conditions such as postural disorders or work-related musculoskeletal disorders (WMSDs) can hinder movement for some construction workers (Khan et al., 2018).

Moreover, the introduction of new technologies often disrupts established workflows and necessitates extensive training to ensure safe usage and mitigate potential health and safety risks (Xi et al., 2019). For instance, while SAM Bricklaying robots offer the potential to perform tasks of multiple workers, they still require human oversight, increasing operational risks associated with machinery use. Improperly designed or operated robots in environments like construction sites can pose significant safety risks to human workers, as highlighted by Liang et al. (2020). In such high-risk settings, the ability to promptly assess and respond to risks in real-time is crucial, yet challenging if the robotic systems lack the necessary design features for such functionality. Moreover, robots employed in construction must navigate and avoid collisions with other robots, workers, and equipment, adding another layer of complexity to their operation. This challenge underscores the importance of designing robotic systems equipped to handle such scenarios effectively.

Additionally, ensuring the safety of human workers in proximity to robots is paramount. Robots need to be meticulously designed to minimize the risk of injury to humans, a task that becomes daunting if the systems are not explicitly engineered for this purpose. Addressing these safety concerns requires careful consideration during the design and operation of robotic systems, as emphasized by Ogundipe et al. (2022). Other studies have looked into the usability requirement of new technology, which often requires existing staff to upskill their knowledge on the use of the new machinery or innovation (Nnana et al, 2019). From this lens, the duration and technicality required to learn and socialise the use of a particular piece of technology can significantly affect perception of its use and ultimately the motivation for its uptake.

3.6.6 Technical Limitations

Technical limitations relate to the performance and capabilities of robots compared to human workers, as they are not entirely autonomous machines with to ability to perform certain tasks (Tan et al, 2020). For instance, sensing and perception robots need humans to function in unstructured and dynamic environments, which can be challenging for their sensors and perception systems (Martins et al, 2020). This is because construction tasks often require a high degree of dexterity and precision, which can be difficult for robots to achieve as construction sites are often rugged and uneven, which can make it difficult for robots to navigate and move around (Oscar et al, 2018). Also, construction tasks often require a high degree of strength and endurance, which can be difficult for robots to achieve.

Furthermore, sites often have harsh conditions such as dust, dirt, and extreme temperatures, which can negatively impact the robot's performance. While there are many robots with different capabilities, not many are capable of being used to work at height with the same ease as human workers (Xu et al, 2019). This is due to interoperability and integration needed for these robots to be able to interact and integrate with other systems, such as building information modelling (BIM) and construction management software, which can be challenging (Wang et al, 2020). Also, robotic systems in construction often have to communicate with human workers, which can be challenging given the complexity of the tasks and the necessary level of coordination (Chang et al, 2020).

3.6.7 Legal and Regulatory Barriers

Legal and regulatory challenges pose significant barriers to the deployment of robots, encompassing concerns related to job displacement and safety. Job displacement is a major apprehension, as robots are often viewed as potential threats to employment security. Consequently, this perception can trigger legal and regulatory impediments to their deployment. Moreover, the lack of liability for robots in case of accidents or malfunctions further compounds regulatory barriers to their adoption (Simeos et al., 2021). For example, enforcing data privacy laws and regulations on robotic systems within construction sites presents a formidable challenge. Similarly, ensuring compliance with intellectual property laws and regulations can be daunting, particularly if the systems are not inherently designed to meet such requirements. Additionally, navigating environmental regulations and local ordinances, which vary across regions, poses compliance challenges for robotic systems not inherently configured to accommodate such diversity (Fusch et al, 2020). Moreover, adherence to international trade laws and regulations adds another layer of complexity to the deployment of robots in construction settings.

3.6.8 Scalability

Scalability, in the context of construction robotics, refers to expanding the use of robotics and meeting construction demand, allowing both small and large construction stakeholders to access these technologies for everyday work (Aghimien et al, 2019). Unlike in the manufacturing and service sectors, where robots are often miniaturized and tailored to fit specific environments, construction robots tend to be more capital-intensive and require multiple units to perform various specialized tasks, making scaling up more challenging. A recent report indicates that many small stakeholders in the construction industry perceive the use of advanced robotics in construction projects as difficult to attain, reinforcing the notion that robotics is primarily accessible to larger companies (Reeds, 2023). This mirrors reports suggesting a decline in robotic installations across the UK, with a 7% drop to 2,054 installations in 2022. This figure places the UK at the 24th position globally in robot density rankings, with the country being the only G7 member outside the top rankings. Interestingly, countries such as Slovenia, Slovakia, Finland, and Hungary demonstrate higher potential for the use of robotics compared to the UK (Gleeds et al., 2023). While various factors may contribute to this disparity, it's noteworthy that the barrier to entry has been identified as a significant hindrance. Despite the UK's technological advancement on par with other nations, the construction industry lags in the adoption of robotic technology and automation.

While it is recognized that the adoption of automation and robotics in construction is still in its early stages, initial indications suggest a growing interest and a noticeable shift in how construction stakeholders are considering the use of robotics in the industry (Delgado, 2019). However, a key question arises regarding scalability – to what extent can robotics be widely implemented in the construction industry and replace traditional construction methods for large-scale projects? According to data from the International Federation of Robotics in 2022, out of 517,000 installations of robotics globally, less than ten percent were in the construction sector (IFR, 2022). One of the factors identified as slowing down the uptake of robotics in construction is technology demand and scalability (Wang, 2022; Chu et al., 2023).

3.6.9 Research and Development Gap

Current research efforts highlight the increasing relevance of robotic technology in the contemporary construction landscape, signalling its adaptive integration into this domain (Ononosen et al., 2023). While significant progress has been achieved in robotics and human-robot interaction within the manufacturing sector, studies focusing on their application in architecture, engineering, and construction (AEC) remain limited (Aghimien et al., 2019). Existing literature predominantly originates from the United States and China, with Europe following suit, while studies specifically addressing robotic innovation in the UK construction sector are comparatively sparse. This underscores the need for expanded research initiatives and exploration within the UK context to fully grasp the potential of robotic technology in construction beyond broader discussions surrounding its utilization.

Ononosen et al. (2023) attribute the scarcity of studies to various factors, including insufficient funding and research and development efforts in robotic innovations, which are essential for industry advancement. Additionally, the absence of clear policies in the UK and globally regarding human-robot collaboration in construction further contributes to this gap (Sharma et al., 2020; Ononosen et al., 2023). This limited research landscape reflects the challenges within the construction sector, where prevailing industrial practices hinder the adoption of robotics (Ajoudani et al., 2021).

Table 4: Leading research institutions in construction automation

Country	Institutions/Universities
United States	North Carolina State, Georgia Tech, Stanford
Canada	Universities of Alberta and Waterloo
South Korea	Yonsei, Hanyang, Inha, Chung-Ang, and Korea Universities
China	Tsinghua and Ningbo
Japan	Osaka and Keio
Australia	UT and Western Sydney
UK	Loughborough and the University of Central Lancashire
Switzerland	ETH
Spain	Carlos III Madrid University
Germany	RWTH Aachen, Technical University Munich

Source: Hoeft et al, (2022).

The industry's competitive nature, characterized by both small and large firms, coupled with the substantial upfront and maintenance costs associated with robotic technology, often outweighs the perceived benefits, leading to a reluctance to adopt innovative approaches (Aghimien et al., 2019). Current research efforts have focused on how cost of procuring and maintaining robotics can be achieved particularly for small companies in the construction space, however, the burgeoning question have centered on the supply chain dynamics of materials needed for production and the imperative for the development of laboratory to test some of these innovation systems in the UK (Ononosen et al, 2023).

The United Kingdom Research Institute, focused on the development of robotic systems and their applications, has a strategic focus on researching robotics across various sectors in the UK. Despite the UKRI Challenge Funds allocating substantial seed funding (£45.5 million) to accelerate research efforts, the concentration remains primarily on four priority areas: nuclear robotics, AI, and robotics in transportation and services. Unfortunately, there is limited investment or research emphasis on the construction sector.

In addition to the UKRI, other research investments in the UK include the UK Robotics and Autonomous Systems (UK-RAS), which currently oversees research activities and fosters collaboration between academia and the broader robotic community to promote greater engagement with robotics (UK-RAS, 2020). The RAS2020 strategy outlines key guidelines for improving the UK's research and industrial base to coordinate the development of assets that would enhance competition and collaboration between researchers, innovators, and industry experts. Despite these initiatives, investment in construction robotics is not progressing at a comparable pace to other sectors in the UK. While the UKRI's national research hub has focused on various core areas such as automated transportation, manufacturing, space, nuclear, agriculture, and healthcare, there is limited prioritization for the construction sector (Gleeds et al., 2021). Although some intersections exist between current investment and research priorities and construction robotics, such as automated transportation's potential to reduce the construction industry's carbon footprint, there is insufficient focus on enhancing safety efforts in future robotics research and investment (Ajadu et al., 2022).

One of the significant barriers to robotic adoption is the issue surrounding intellectual property rights and management. While universities often support research and development in robotics, they also typically seek a share of the resulting intellectual property. This desire for ownership can hinder industry development of robotics (Saung et al., 2021). Moreover, research findings indicate that researchers often lack a comprehensive understanding of existing commercial industries essential for advancing robotics for commercial use (Xu et al., 2022). This highlights the challenge of aligning research efforts with industry needs. Additionally, there is a disconnect between industry developments and academic research, reducing cohesion across the overall RAS ecosystem. This lack of collaboration impedes the translation of research findings into practical applications in the construction sector.

Table 5: Summary table of barriers to robotic adoption

Barrier to robotic adoption	Explanation
1. Research gap – innovation pace vs responding to industry needs	• Limited investment or research emphasis on the construction sector.
2. Upfront cost	• Substantial upfront and maintenance costs associated with robotic technology often outweigh the perceived benefits, leading to a reluctance to adopt innovative approaches.

	• Current research efforts have focused on how the cost of procuring and maintaining robotics can be reduced, particularly for small companies in the construction space
3. Scalability	• Unlike in the manufacturing and service sectors, where robots are often miniaturized and tailored to fit specific environments, construction robots tend to be more capital-intensive and require multiple units to perform various specialized tasks, making scaling up more challenging.
4. Legal and Regulatory	• The lack of liability for robots in case of accidents or malfunctions further compounds regulatory barriers to their adoption • Enforcing data privacy laws and regulations on robotic systems within construction sites • Ensuring compliance with intellectual property laws and regulations can be daunting, particularly if the systems are not inherently designed to meet such requirements. • Navigating environmental regulations and local ordinances, which vary across regions, poses compliance challenges for robotic systems not inherently configured to accommodate such diversity.
5. Technical barriers	• Due to interoperability and integration needed for these robots to be able to interact and integrate with other systems, such as building information modelling (BIM) and construction management software
6. Lack of standard	• Lack of product standard impacts construction stakeholders' perception of which robotic technology is best suited.
7. Usability and adaptability	• All robots are not amenable and malleable to work in certain conditions as humans.

3.7 Geopolitical perspectives of Robotics Technology Adoption and the UK

An examination of robotics adoption in the UK must take into account the geopolitical factors influencing its uptake. These external factors, including macroeconomic and political dynamics, significantly impact the extent to which the UK embraces robotics in its construction sector. Despite notable advancements, particularly in other industries, robotics adoption remains relatively low in the UK's construction sector. According to the Department for Business, Energy and Industrial Strategy (BEIS) 2021 report, the UK trails behind other advanced economies in terms of robotics adoption.

In 2015, the UK utilized 71 robots per 10,000 employees in manufacturing, ranking 22nd globally and 15th in Europe. Although this figure has doubled to 141 robots per 10,000 employees (equivalent to 1 robot per 71 employees), it still falls short compared to OECD and EU counterparts. Estimates suggest an even lower adoption rate in the construction sector, with just 1 robot for every 200 employees in the UK (Chang et al., 2023). In comparison to leading countries, the UK's robotics adoption rate is significantly lower. For instance, the Republic of Korea boasts 766 robots per 10,000 employees, Singapore 556 robots, Japan 507 robots, and Germany within the EU 364 robots per employee (Finlay et al., 2023; Wu et al., 2023). These figures underscore the substantial gap between the UK and other nations in integrating robotics into its construction industry, indicating a considerable distance to cover in catching up.

Countries are fiercely competing in the realm of modern construction methods, with Japan leading the charge in robotic and MMC utilization, surpassing the entire UK. Notably, Malta in Europe stands out for its robust adoption of robots, while the UK currently ranks 15th. The International Federation of Robotics (IFR) uses robot density, indicating the number of robots per 10,000 workers, as a key metric. Globally, robot density nearly doubled from 66 units in 2015 to 126 units in 2020, with a significant spike from 113 units in 2019 to 126 units in 2020 alone (International Federation of Robots, 2021). Asia is currently the continent with the highest density of robots worldwide, this is followed by Europe, then the Americas (IFR, 2021). The ten most automated countries in the world are South Korea, Singapore, Japan, Germany, Sweden, Hong Kong, the United States, Chinese Taipei, China, Denmark, and Italy (IFR, 2021). The UK is not in the top 20 most automated countries in the world (Gleeds et al, 2022).

The geopolitical implications of robotic advancement in construction projects have sparked a growing debate. This discussion is fueled by the complex nature of innovation as nations strive to enhance productivity, drive economic development, and navigate the intricate dynamics of the robotics supply chain integration into various industries. Currently, countries like Japan, China, the US, and Germany lead the global adoption of robotics (Kim et al., 2022). In the context of globalization, this trend is reshaping the competitive landscape. Nations competing for global leadership in robotic innovation are expected to trigger shifts in various aspects, including raw materials sourcing, technology transfer, and proprietary technology ownership. These changes carry significant economic and competitive implications (Pan et al., 2022). Countries making strides in construction automation are better positioned to export these technologies, giving them a crucial edge in the global market.

As highlighted by the United Nations Center for Policy Research (2021), the intersection of AI with affective computing, cyber and biotechnologies, robotics, and additive manufacturing presents intricate global implications that remain poorly understood. This lack of comprehension leaves the multilateral system with limited tools to anticipate and mitigate emerging risks. This issue is particularly pronounced because the convergence of AI and robotic innovations extends beyond the realms of social, economic, political, and security considerations. It also gives rise to systemic vulnerabilities that must be anticipated and addressed, especially in the context of evolving cyber risks.

As Alexandre (2017) asserts, the convergence of vast databases, increasingly powerful computers, and machine-learning algorithms, primarily driven by American and Chinese digital giants, has propelled artificial intelligence forward at a surprising pace, even exceeding the expectations of its proponents. Moreover, there's a looming risk that as the geopolitical dimensions of robotics become more pronounced, it will give rise to a new technological complex, reminiscent of the slogan "Robots for jobs, life for us," highlighting the specialization of these robots (Wu et al, 2023). This suggests that countries with advanced robotics capabilities are better positioned to steer the integration of AI and control the resulting data. The evident geopolitical reality is that countries remain wary of technologies that are not proprietary and are concerned about how these technologies might be utilized or integrated into the construction space, especially if there are suspicions of data breaches. For example, the Huawei case and the current crackdown on Chinese technology in the US may prompt the UK, as an ally of the United States, to follow suit (Bretton et al, 2021).

While the UK is emerging as a contender in the global race to adopt robotics in construction, drawing on its strengths in innovation, engineering, and research and development (Segay et al., 2021), it lags in comparison to its counterparts in the OECD, Europe, and the world. Factors such as age, skills, technological perception, and investment dynamics vary across countries and play crucial roles in shaping their adoption of robotics. In this competitive landscape, the UK faces formidable competition from nations like China, the United States, and Germany, which have made substantial investments in robotic construction technologies. To bridge this gap and catch up with global advancements, the UK must accelerate its efforts in robotic innovation. It's not a matter of if robots will revolutionize the industry, but rather when they will become pivotal in determining leadership in the new era of robotics (Finbarr et al., 2022). Despite this challenge, British companies and research institutions are at the forefront of pioneering advancements in robotic construction technologies. These innovations include robotic bricklaying, autonomous drones for site monitoring, and robotic exoskeletons for worker assistance.

Another critical aspect to consider is the technological dependence, intellectual property rights, and strategic partnerships involved. However, the adoption of robotics also offers the UK significant opportunities to boost its global competitiveness, foster innovation, and generate new employment prospects in high-tech sectors. It should prioritize the advancement of homegrown robotic technologies and capabilities to uphold technological sovereignty and diminish dependency on external suppliers. Achieving this necessitates continuous investment in research and development, along with strategic collaborations with both industry and academia.

3.8 Chapter summary

This section provides a comprehensive exploration of the primary issues hindering robotic adoption in the UK, aiming to uncover deeper insights into the challenges at hand. The UK is lagging behind other countries in terms of its robotic capabilities and adoption rates. While there are government initiatives aimed at increasing the use of robotics, including proposed investments in laboratories, research projects, and robotic innovations, much of this investment is directed towards other sectors such as manufacturing and services. One of the key findings of this chapter is that despite the construction industry in the UK traditionally being considered low-tech, advancements in technological innovation are signalling a shift. The ecosystem of innovation is primed to accelerate the adoption of robotics in the UK construction sector. Therefore, there is a pressing need for a policy reset and a paradigm shift away from conventional construction methods towards a more digitized and robotized future, fostering the emergence of robotics within the industry.

Another key revelation from this chapter is that the barriers to adopting robotic technology in the UK construction industry stem from both internal and external factors. Internally, these barriers encompass limitations that must be systematically addressed within the UK construction industry before meaningful progress can be achieved. One such internal factor is the perception of construction stakeholders, which serves as a pivotal gauge of readiness and willingness to embrace robotics. This perception forms a crucial barrier to adoption.

Furthermore, internal limitations also include the significant upfront costs associated with robotics implementation. Despite the acknowledged utility of robotics in enhancing health and safety standards, the substantial financial investment required for procurement and implementation poses a major hurdle for many construction stakeholders. This financial barrier significantly impacts the feasibility of adopting robotic solutions. Additionally, interconnected considerations such as usability, scalability, affordability, and equity further compound the challenges surrounding robotic adoption. These factors contribute to an ongoing discourse on the equitable integration of robotics and continue to shape the dialogue on how this technology can effectively navigate the dynamic and evolving landscape of the UK construction industry. Also, the widespread adoption of these robots remains limited due to scalability and resilience concerns, especially when considering the competitive resources of small versus large companies within the industry. This section, nonetheless, offered a comprehensive analysis of the existing robotic technologies and their functions. It delved into the complexities of robotic technology adoption within the UK context, aiming to unveil the primary factors influencing its architecture, uptake, and the current landscape.

While internal factors play a significant role, the external drivers also exert a considerable influence, shaping the adoption of robotics in the construction industry. These external drivers encompass the intersecting impact of policy, consumer perception, and government directives on the construction sector, shaping the trajectory of robotics adoption. Among these external factors, the economic implications of robotics stand out prominently. Concerns arise regarding the potential for widespread adoption of robots, coupled with AI and other digital innovations, to result in unemployment and limit opportunities for skill development among construction workers. It also surveyed the landscape of robotic industries in the UK, focusing on their relevance to construction. It was revealed that while several robotic innovation and research centers exist, most laboratories lack specialization in construction robotics, limiting the scope of potential innovations in the field.

The central argument of this chapter underscores that while robotics is gaining momentum, a multitude of external factors beyond the immediate control of construction stakeholders significantly impact adoption rates. However, upon conducting a cost-benefit analysis of adopting robotics, it becomes evident that the benefits outweigh the drawbacks. Despite the challenges posed by external drivers, embracing robotics emerges as an inevitable pathway for advancing the industry, driving efficiency, and enhancing productivity. The section further delved into a sub-analysis of the geopolitical perspectives shaping robotics adoption not only at the international level but also within the UK. It emphasized the significant impact these perspectives have on shaping the UK's adoption of this technology and the potential gains it offers. While competition exists locally, international dynamics carry profound consequences, particularly concerning exports, technology transfer, software issues, and other complexities inherent in technological skill development. These factors serve as disincentives that hinder the acceleration of adoption at the industrial level.

The chapter determined the lack of clear regulations and legislation that incentivise the adoption of robotic technology for the prevention of construction-related injuries in the UK. Neither is there an evident roadmap detailing how the government intends to achieve some of its blueprint targeted to encourage robotic adoption. Where stated, these plans are not specifically tailored to the construction industry, and there is limited bandwidth to ascertain the degree to which stakeholders (in the construction industry in the UK were incorporated in the process. These yawning gaps leave room for further exploration and underscore the need for an in-depth analysis of the views/perceptions of stakeholders in the UK construction industry on how these technologies can be utilised in the prevention of injuries and in articulating a roadmap for their adoption. Next, the thesis explores the types of construction injuries, the role of robotics in their prevention, and health and safety regulations in the UK construction industry.

CHAPTER FOUR: Construction Injuries, the Role of Robotics and Health and Safety in the UK

4.1 Introduction

Construction is considered one of the most hazardous industries in the UK, with a high rate of accidents and injuries. According to the Health and Safety Executive (HSE), in 2019/2020, there were an estimated 142,000 injuries to workers in the construction industry, of which approximately 2,500 were fatal and approximately 140,500 were non-fatal (HSE, 2021). Some specific statistics regarding construction-related injuries in the UK include according to the HSE, falls from height are the most common cause of fatal injuries in the construction industry, accounting for approximately 40% of all fatal injuries in 2019/2020 (HSE, 2020).

Slips, trips, and falls are the most common cause of non-fatal injuries in the construction industry, accounting for approximately 25% of all non-fatal injuries in 2019/2020 and over 20% of all reported injuries caused by manual handling. In 2019/2020, there were 40 fatalities in the construction industry in the UK. Same period, there were 38,000 reported injuries in the construction industry in the UK, with over half of them resulting in more than 7 days of absence from work (ONS, 2022). The number of self-reported injuries in the construction industry in the UK is likely to be significantly higher than the official statistics, as many injuries go unreported (HSE, 2020).

Current data from the Health and Safety Executive reveals that more than 64000 construction workers sustain construction-related injuries yearly (HSE, 2022). This figure does not include underreported cases – hence potentially higher than stated (Gleeds, 2021). According to recent data, non-fatal injuries cost the UK construction industry more than £1.29 billion (Lu et al, 2022). Beyond the economic implications of construction injuries and fatalities, including loss of human lives, the legal consequences of paying out compensation and loss in the number of workdays and accident days are critical considerations that exacerbate the impact of construction injuries in the UK (Haupt et al, 2019).

In a report, McKinney determined that the direct cost of dips in performance and productivity, project delays, increased leakages, and the cost of construction projects (McKinney, 2019). For instance, HSE found that the cost of ill health and injuries in the UK construction industry costs between £963 and £1,476 million per year (HSE, 2022). The central estimate cost of non-fatal injuries is estimated to cost the construction industry alone more than £659 million, which exceeds manufacturing (£658 million), transportation (£322 million), and is nearly thrice the estimates for agriculture (£199 million) (HSE, 2021). These numbers are concerning as going by the Heinrich triangle model, the risk of fatalities correlates with the number of non-fatalities, implying the higher the latter, the higher the former (Brown et al, 2018). For instance, the HSE reports that the worker fatality rate in the UK for its workers is currently 1.3 per 100,000 (HSE, 2018). While this number is significantly low, it is three times the average rate across all non-fatalities for worker injuries in the UK in the construction sector.

While there has been a significant decrease in non-fatal injuries reported in the UK over the past decade, a concerning number of accidents and injuries persist annually, encompassing fractures, amputations, falls, scalping, scalding, musculoskeletal diseases, and weather-related ailments due to exposure to harsh conditions (Gleeds et al., 2021). The risk of non-fatal injuries in the UK construction industry is notably higher for men than women, with a reported estimate of 395 per 100,000 male workers compared to 52 per 100,000 female workers (PHE, 2020; HSE, 2020). Recent data from the HSE indicates a slight increase in fatalities among UK workers over the past two years, rising from 1.36 per 100,000 in 2018/19 to 1.84 per 100,000 in 2020/21 (HSE, 2022). This trend is correlated with the predominance of men in the UK construction industry compared to women (Newman et al., 2021). In the next paragraphs, the main sources of construction injuries in the UK are examined in greater detail.

4.2 Major causes of construction injuries in the UK

4.2.1 Fall from heights

Falls are regarded as the leading cause of injuries in construction-related accidents, injuries (48%) and fatalities (30%) (Xu et al, 2018). It represents more than one-third of all the injuries reported in the industry and is a leading cause of death (Jebelli et al, 2019). Recent data reveal that falls from heights in construction sites were the leading cause of fatalities and construction injuries in the UK (Newman et al, 2021). A report by Construction Management UK (2021) reveals that slips, trips, and falls account for one of the highest causes of non-fatalities in the construction industry. Falls were the cause of the most fatalities to men in the UK (20) in the construction industry, based on data by HSE for 2020/21. This was two times higher than the number of fatalities caused by being struck by an object (9).

Relatedly, the Centers for Disease Control (CDC) determined falls to be the number cause of construction workers' fatalities globally, accounting for 401 fatalities of the 1102 construction total fatalities (CDC, 2021). Apart from the financial burden and life-changing health impacts associated with falls, it can lead to deaths and demoralisation of construction work, including stoppage of construction when there is a violation of processes (Chu et al, 2018). Recent research indicates that the risk of falls is increased three times for workers with less than one year of experience than those with more (Guo et al, 2020). Lack of experience, poor health and safety practice and compliance, conflict, and lack of training on the use of PPEs and harnesses can triple the risk of falls and fatalities in the construction sector (Haddon et al, 2019).

Available studies have explored the factors accounting for the predisposition of construction workers to falls. Hu et al (2019) found an association between individual activities, environmental conditions, management policy, and site conditions as critical factors increasing susceptibility to falls. Individual variables such as the physiological, demographic, and perception of risks can impact how an individual prevents their exposure to fall risk (Chu et al, 2018). Management policy regarding falls can affect its outcome (Wang et al, 2018). Company size has been found to correlate with the risk of fall accidents, with smaller companies having a higher propensity to have workers with fall exposure than those in bigger companies (Onibade et al, 2020). This has been linked to the employment period, wages, improper safety measures and PPEs as well as PFAS in small companies (Wang et al, 2018). Contrary studies, however, fault this position (Ryu et al, 2019). The attitude of management towards ensuring safety measures are in place has a key impact on the prevention and incidence of falls (Abdulrahman et al, 2019). This is against the backdrop of the role they play in health and safety management, enabling the right work conditions and in preventing accidents and other hazards on the construction site, including the use of PPE and PFAS.

4.2.2 Overexertion

Overexertion stands as the second leading cause of workplace injuries and accidents (Taylor, 2020), largely stemming from continuous physical tasks like lifting, pushing, holding, and carrying objects on construction sites—ranging from excavation and compaction to material and equipment movement—putting workers at risk of injury and even fatalities (Kim et al, 2019). This factor is a key contributor to work-related musculoskeletal disorders (WMSDs) among construction workers (Health and Safety Executive, 2019), with an estimated 90% of construction activities involving manual handling, increasing susceptibility to WMSDs and contributing to construction-related injuries in the UK (Kaur et al, 2019). Overexertion injuries rank second among occupational injuries and accidents, elevating the risk of MSDs characterized by swelling of limbs, tendons, ligaments, and muscles (WHO, 2020). Beyond immediate impacts like lost work hours, these injuries can lead to repetitive stress movements and chronic health complications (Macquinious et al, 2019).

Overexertion injuries pose a significant risk to construction workers in the UK due to the manual labour and repetitive motions inherent in construction work. According to the Health and Safety Executive (HSE, 2022), overexertion injuries accounted for approximately 30% of all reported injuries in the UK construction industry in 2019/2020. Specifically, manual handling is a significant contributor to overexertion injuries among construction workers, with over 20% of reported injuries attributed to this cause. Sprains and strains are the most common types of overexertion injuries among construction workers, representing approximately 60% of all reported cases (Rhu et al, 2022). Furthermore, HSE reports indicate that overexertion injuries are more prevalent among older workers, particularly those aged 45 and over, compared to younger counterparts, and men are more susceptible than women. Additionally, overexertion injuries often result in long-term absence from work, with an average of 18 days lost per case in the construction industry (Fuentes et al, 2022).

4.3 Age-associated Musculoskeletal Disorders (MSDs)

Musculoskeletal disorders (MSDs) pose a significant health risk to construction workers in the UK, comprising over 50% of work-related ill health cases, as reported by the Health and Safety Executive (HSE) in 2019. These disorders have resulted in more than 40,000 reported cases in the UK, statistically surpassing other industries, as noted by Miller et al. (2019). The World Health Organization (WHO) also identifies MSDs as a leading cause of disability worldwide, limiting mobility, increasing the risk of early retirement, and reducing overall well-being levels (WHO, 2020). Back pain is the most prevalent form of MSD among construction workers, accounting for around one-third of all cases, according to the HSE. Upper limb disorders, including conditions like carpal tunnel syndrome and tendinitis, contribute to approximately one-quarter of all MSD cases in this workforce.

Furthermore, the HSE highlights that older workers, particularly those aged 45 and above, are at a higher risk of experiencing MSDs compared to their younger counterparts, and men are more susceptible than women (HSE, 2021). Additionally, MSDs frequently lead to long-term absences from work, with an average of 18 days lost per case within the construction industry, according to the HSE's findings in 2020.

MSDs encompass a range of medical conditions, including osteoarthritis, traumatic fractures, osteopenia, and an increased risk of inflammatory diseases, with acute cases even posing a danger of amputation, as highlighted by Umer et al. (2016). The WHO associates MSDs with various other conditions, such as connective tissue disease, joint impairment, reduced mobility, pain, and degeneration of adjacent connective tissue, ultimately diminishing affected individuals' work capacity and predisposing them to opportunistic diseases related to musculoskeletal health (WHO, 2019). MSDs represent a group of conditions affecting muscles, tendons, ligaments, nerves, and soft tissues, often leading to pain, discomfort, and restricted movement in the affected areas. They frequently result from repetitive motions, prolonged periods of inactivity, poor posture, and similar factors. Workers in construction and other occupations involving repetitive motions or extended periods of sitting or standing are particularly susceptible to MSDs. Common types of MSDs include Carpal Tunnel Syndrome, characterized by numbness, tingling, and weakness in the hand and fingers due to pressure on the median nerve in the wrist; Tendinitis, involving inflammation of a tendon leading to pain and stiffness; Bursitis, marked by inflammation of a bursa causing discomfort; Tennis elbow, presenting as pain and tenderness on the outer part of the elbow due to overuse of forearm muscle tendons; and Low back pain, which manifests as discomfort in the lower back, often stemming from strain, injury, or spinal degeneration (Anderson et al., 2021).

In the UK, MSDs account for about 20% of all injuries and illnesses in the workplace (Graham et al, 2020). It is one of the main causes of absenteeism in the construction industry and a contributory factor for project delays, lost time, and indirect costs (Chu et al, 2019). Biomedical risk factors include awkward postures, repetitive movements, and overexertion (Moore et al, 2018). Several ergonomic risk assessment techniques have been identified in the literature including self-reported methods, observational-based methods, vision-based methods, and direct measurement methods (Wang et al, 2015). These methods altogether provide accurate, non-invasive, automated human motion data for analysing behaviour patterns that constitute unsafe practice in the workplace (Han et al, 2019). This is not discussed further in this thesis so as not to shift the focus of the analytical premise.

4.4 Construction Robotics and Human: A Nexus

Scholarly investigations persistently delve into the feasibility and benefits of augmenting human-robot collaboration (Bock, 2019; Carl et al., 2020). Contention arises regarding whether robots should operate autonomously, tackling repetitive tasks that heighten workers' susceptibility to injuries (Morten et al., 2019; Xu et al., 2021). Alternatively, discourse centers on integrating robots into human functions within construction settings. This approach involves deploying robots like exoskeletons in high-risk areas to augment these functions (Sinkonnen et al., 2019). However, this integration introduces new risks, such as health and safety hazards in cases of non-compliance (Bobden et al., 2020). Consensus on the extent and manner of robot integration into construction work hinges on factors like type, functionality, skill requirements, technical complexity, and associated costs. Another facet of the discussion revolves around bolstering construction resilience against shocks and urbanization effects, including evolving stakeholder preferences. The perspective emerges that robots have the potential to modernize, automate, and enhance efficiency while potentially reducing long-term costs due to fewer accidents, near misses, and injuries resulting from fatigue and strain inherent in traditional infrastructure delivery approaches.

The realization of human-robot collaboration and integration depends on multifaceted factors extending beyond mere adaptation to encompass key issues like achieving mutual benefit, sustainability, and the capacity to perform tasks autonomously or semi-autonomously (Green et al., 2021; Fain et al., 2021). Additionally, the optimization, automation, and modernization of these tools, coupled with the integration of new and emerging technologies like IoT and machine learning, play a crucial role in determining their efficacy and adaptability to rapidly changing demands (Darlow et al., 2022).

Numerous studies in the literature have delved into the potential of human-robot collaboration within the construction industry, aiming to mitigate workers' exposure to injuries and fatalities. One avenue explored involves automating high-risk functions and enhancing traditional construction methods with modern approaches to minimize labour-intensive tasks. For instance, robots can replace humans in fabrication, molding, and earthworks, while lower-risk activities such as additive manufacturing and autonomous systems can leverage human-robot collaboration to enhance productivity (Kasperzyk et al., 2017; Bogue, 2018; Aghimien et al., 2019; Gharbia et al., 2020).

Another approach entails developing specialized human-robot teams focused on communication and interface interactions to improve the design and integration of robots into construction processes. This fosters greater trust, co-dependence, and seamless fusion between humans and robots, ultimately enhancing safety and preventing injuries on construction sites (Liu et al., 2021). The critical importance of trust in such collaborations lies in averting the risk paradox: without trust, manoeuvring and coordinating activities between humans and robots can inadvertently increase injury risks rather than mitigate them (Hamburg et al., 2020; Xiang et al., 2019; Dobra and Dhir, 2020). Furthermore, there's a need to address the aspect of robots undertaking risky construction activities requiring human oversight to ensure safety compliance. Despite their precision, robots are susceptible to malfunctions and errors, posing potential health and safety risks on construction sites. Therefore, human supervision remains essential to mitigate these risks and ensure the overall safety of construction projects (Sellner et al., 2019).

Another promising avenue involves integrating robots to enhance construction safety by mitigating physical strain and hazardous activities. This encompasses leveraging robots to alleviate the bodily pressures resulting from strenuous tasks (Bademosi et al., 2021). Furthermore, robotic design holds potential for integrating essential functions into core construction processes, including sensor utilization, computer vision, assembly, health and safety information systems management, object and hazard identification and prevention, as well as integration with Building Information Modelling (BIM) (Xiang et al., 2021).

In the realm of robotics applied to construction, scholars emphasize the crucial attributes of resilience and adaptability (Zieba et al., 2019; Shu et al., 2022). Resilience, defined as a robot's ability to effectively respond to its intended design purpose without errors resulting from parallax, technical failures, or susceptibility to human error during core functions execution, is paramount (Shu et al., 2022). This concept intertwines with adaptability, which refers to a robot's capacity to fulfil its core functions without breakdowns or increasing the risk of health and safety hazards (Reed et al., 2022). Industry design adheres to these fundamental principles, but the extent to which robots demonstrate such capabilities in performance within the built environment remains a central concern. Argan et al. (2019) contend that this intersects with the concept of reliability and perception, with the former being a critical determinant of whether humans can trust that robots will function at the expected level reliably.

In pursuit of reliability, Zieba et al. (2019) assert the necessity of achieving certain parallels. This involves incorporating systems into the design and implementation phases of robotics in construction to minimize risks. It also entails tailoring the design process to enable reactive and adaptive functions within robotic systems to mitigate the risk of further harm in the event of technical errors. This aspect has become pivotal in human-robot design, serving as a defining factor in determining the extent, scope, and dependability of humans working alongside robots to accomplish various tasks in the construction industry. However, this raises a pressing question regarding the autonomy and semi-autonomy of robots.

The emergence of automation in the construction industry carries considerable significance. Recent advancements in robotic systems demonstrate an increasing capacity for autonomous operation in construction tasks, often with minimal human intervention (Singh et al., 2019). While full-scale automation has been achieved in sectors such as manufacturing and industrial applications, its implementation in construction is still evolving. Studies have identified various clusters representing potential applications of robotics in the construction sector. One such cluster is robotic automation, which involves the use of machines or technology to execute tasks (Moora et al., 2016). In full automation, machines perform functions based on programmed algorithms without human intervention. Semi-automation, on the other hand, allows for human intervention to some extent, despite tasks being executed based on programmable algorithms (Agadu et al., 2017). It is essential to recognize that automation spans a spectrum from flexible to integrated, fixed, and programmable, contingent upon the complexity and functionality of the machine. Lundeen et al. (2017) elucidated various methods for enabling autonomous sensing and modeling of construction objects, crucial for their adaptability to diverse circumstances and ensuring high-quality work delivery. Resilience and the ability of collaborative robots to operate effectively in unforeseen situations emerged as pivotal factors in the study. Additionally, the extent to which robots fulfil predefined objectives is crucial for mitigating safety risks and enhancing overall architectural, engineering, and construction quality.

Robot resilience refers to a robotic system's ability to recover following partial or total system damage (Zhang et al., 2017). In the construction environment, where partial system damage is common, maintaining robot functionality at a desired level is crucial. Resilience in robots is underpinned by four core principles outlined by Hollnagel et al. (2014): self-healing, self-repairing, sustainability, and reliability. Self-healing, analogous to biological processes, enables robots to recover and adapt to new states following external impacts on their functionality. This concept draws parallels with biological cells' regenerative capacity to adapt in response to external stimuli. However, Hollnagel acknowledges a dichotomy between biological and mechanical systems, highlighting self-healing as a binary element in robots' functionality beyond damaged components (see figure below). This underscores the importance of manufacturing robots with resilience in mind to ensure autonomous operation and operational efficiency.

Fault-tolerance is a fundamental concept in software engineering, referring to a robotics system's ability to maintain its functionality, design, and utility despite faults (Brown et al., 2019). These faults may stem from input errors in software systems or deficiencies in software development rather than inherent manufacturing flaws (Lens et al., 2018). They encompass component damage and the alignment of recovery solutions. The essence lies in robots' ability to continue functioning despite software or hardware faults. However, Wang et al. (2019) argue that the achievability of fault-tolerance depends on how software design is encoded into the functionality of the robot's hardware systems.

Sustainability, within the realm of resilience, emphasizes the repairability of robots and the utilization of redundant parts to replace damaged components (Zhang et al., 2017). It aligns with the concept of survivability, which extends the longevity of robotic parts and ensures their durability, thus enhancing the enduring capacity of robotic systems. Robustness, on the other hand, pertains to a robot's ability to maintain optimal functionality despite internal and external interference or noise, addressing its sensitivity to such disturbances and its capability to sustain operations over extended periods (Wagner et al., 2017). These aspects converge into the crucial element of dependability in robotic systems, defined by Abou et al. (2021) as the user's confidence in a robotic system's ability to fulfill all conditions. This notion resonates with the three merits of robots identified by Sinclair et al. (2018), which encompass cost-effectiveness, repairability, durability, and interconnectivity, essential qualities for both autonomous and semi-autonomous systems.

Another prominent cluster identified in the literature is human-robot collaboration, which serves as a fundamental domain for the utilization of robots within the construction sector. This encompasses various emerging technologies such as exosuits, exoskeletons, support robots, and humanoid robots, employed in diverse capacities within construction, including lifting, support for traditional construction functions, image recognition, and fostering resilience between workers and robots (Paneru et al., 2021). Human-robot collaboration offers a myriad of advantages crucial for adapting to complex and evolving construction environments. According to Zhang et al. (2023), the integration aims to enhance construction productivity by improving team dynamics, cooperation, and addressing unpredictable uncertainties inherent in the construction domain. Furthermore, Furet et al. (2019) noted that one advantage these robots possess over fully autonomous counterparts lies in their decision-making, responsiveness, and adaptability, reducing the challenges associated with robot programming and the level of task execution required by automation. This is significant considering that human workers contribute creatively and navigate uncertainties in complex tasks such as welding, assembly, and structural design, complementing the capabilities of robots.

The evolution of human-robot collaboration extends beyond physical task execution to encompass integration and identification of objects within the construction environment. Ilyas et al. (2021) found that by leveraging perception sensors and intelligent algorithms, robots can detect component installation, generate risk reports, and provide operational status updates, elevating the concept of collaboration with humans to a more sophisticated level. Moreover, Liu et al. (2021) identified brainwave-driven human-robot collaboration in construction, where wearable electroencephalographs capture workers' brainwave patterns. With this data, robots can assess the cognitive load associated with tasks and adapt their performance accordingly. Such advancements offer dual opportunities for robots and humans to enhance their collaboration, improving efficiency, performance, and ultimately resilience in construction operations.

Anna et al. (2021) demonstrated the application of reinforcement learning techniques to enhance the integration of robots with humans on construction sites. Their approach focused on preventing collisions with human collaborators and obstacles, particularly in hazardous zones. Liang et al. (2019) conducted a study in China showcasing the use of this method to train robots for quasi-repetitive construction tasks and to monitor feedback and performance, informing future operations.

In a separate study, Ogunseiju et al. (2021) investigated the utilization of passive exoskeleton robots for material handling and evaluated the neurobehavioural performance of operators. This research aimed to increase their industrial value on construction sites and facilitate autonomous robot skill acquisition. The precision in object identification and design enhancements for safe deployment collectively represent significant strides toward resilience in the construction industry.

Significant progress has been made in the physical integration of robots with humans to enhance productivity, particularly in matching robotic strength, whether mechanical or electrical, with human skills to reduce manual labor in repetitive and hazardous tasks on construction sites (Abou et al., 2021). For example, Semi-Automated Robots can construct walls faster than 10 humans, while the Manual Unit Lift Enhancer and Rebar-Tying Robot excel in lifting and rebar-tying tasks, albeit still requiring human intervention or assistance for optimal performance (Zhou et al., 2019). However, these robots, despite their capacity to outperform humans in certain tasks, highlight the importance of collaboration. Robots cannot operate in isolation but rely on human environments to function effectively. This implies that construction workers and robots engage in direct or mediated physical interactions to execute on-site construction tasks more efficiently and precisely within a shared human-robot collaboration workspace. Nonetheless, workers may experience psychological and physiological challenges from the novel collaborative relationship with unfamiliar robotic partners (Zhang et al., 2023).

Robots play a crucial role in ensuring health and safety on construction sites, addressing the pressing concerns posed by an aging workforce and critical skills shortages (Miller et al., 2020). Ryu et al. (2020) emphasized the need to integrate robots into existing health and safety protocols within construction sites as a method to achieve this objective. However, studies by Xu et al. (2020) and Wang et al. (2021) highlight two dimensions of safety concerning robots in construction. Firstly, robots contribute to enhancing safety by assuming tasks with high susceptibility to construction injuries, thereby reducing human exposure to risky activities (Xu et al., 2020). By providing support for manpower and minimizing human exposure to repetitive or hazardous tasks, robots help optimize the workforce's performance while mitigating injury risks. Secondly, robots themselves perform tasks that expose construction workers to heightened risks, but by substituting humans in these tasks, robots minimize safety vulnerabilities (Xu et al., 2020). This dual approach underscores the role of robots in not only augmenting human capabilities but also directly addressing safety concerns by reducing human exposure to hazardous conditions on construction sites.

Ryu et al. (2020) emphasized the importance of employing objective and systematic methods to assess the impact of semi-automated construction systems on health, safety, and resilience within construction sites. Their study highlighted how systematizing robotic systems increases the likelihood of achieving predictability and normalcy in construction operations. Building on this, Kas et al. (2020) argued that robots can enhance safety protocols by adapting hazard recognition tools and providing onsite-specific training to assess risks effectively. Moreover, the utilization of drones for aerial assessment, as advocated by Colbam et al. (2021), offers a comprehensive view of construction sites, aiding in surveillance, information gathering, hazard management, site planning, and risk mitigation. Zhu et al. (2021) further explored the relationship between trust, communication, and safety in robotic systems, particularly in human-robot interaction contexts. Their study emphasized the crucial role of trust in deploying robots as safety assets, especially when collaborating with humans. Advancements in robotic technology, coupled with digital innovations such as AI, big data, and machine learning, expand the possibilities for achieving greater work integration and ensuring safety in both structured and dynamic construction environments (Wang et al., 2019). These developments underscore the evolving role of robots in construction, not only as tools for efficiency but also as enablers of safer work practices and environments.

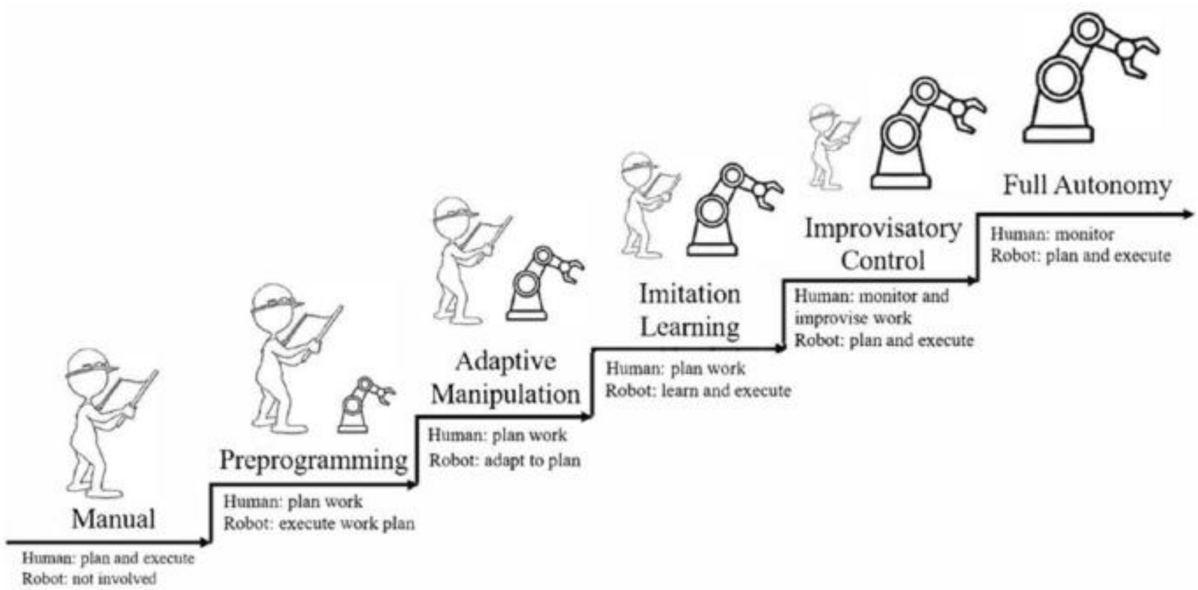

Figure 10: Levels of construction robot automation by Liang et al (2021)

A significant cluster identified in the literature pertains to innovative robotic designs, highlighting robotics as an evolving phenomenon in the construction domain that is poised for continuous growth and transformation of objective reality. Innovations in robotics and novel designs are anticipated to revolutionize the manner and extent to which construction activities are executed in terms of timeliness, spatial utilization, and quality (Aderigbagbe et al., 2021). This includes leveraging robotics for BIM adaptive augmented spatial reality and integrating robotics with artificial intelligence to enhance their functionality and data processing capabilities. This trend is particularly pertinent given the challenges faced by the construction industry, such as labor shortages and escalating housing demands (Chen, 2023).

Current metrics indicate ongoing advancements, with innovations pushing the boundaries of what is achievable. For instance, studies have demonstrated the use of brain-computer interfaces to enhance robots' manoeuvrability and adaptability on construction sites, drawing insights from human-machine collaboration (Liu et al., 2021; Tavares et al., 2022). Furthermore, significant strides have been made in robotic designs, enabling smart construction robots equipped with enhanced capacity, efficiency, and safety features to address industry needs. Robotic sensors, for instance, can assess structural components at a rate of 1,000 times per second, devoid of fatigue-induced errors (Xerxes et al., 2021). Moreover, precision robot construction optimizes machine utilization by minimizing idle time and fuel consumption, thereby reducing greenhouse gas emissions in the construction sector.

4.5 Mingling Middle: Construction and Safety

Effective site safety management is recognized as a crucial measure for saving lives and preventing non-fatal injuries and fatalities on construction sites (Agyekum et al, 2018). Safety risk, defined as the risk of hazard exposure and its severity (Lu et al, 2017), underscores the need for robust safety control measures. Construction sites are inherently dynamic environments, constantly evolving and presenting various risks to workers (Wang & Razavi, 2016). Accidents often occur when workers are exposed to unforeseen risks and lack focus or awareness. Therefore, leveraging technology to detect hazards and promptly warn employees can empower them to take corrective actions and prevent serious accidents (Guo et al., 2017b). For instance, struck-by accidents, a leading cause of severe workplace injuries in the construction sector, can be mitigated through such technological interventions. Chi et al. (2019) conducted a review of 9,358 accidents in the US construction industry between 2001 and 2011, revealing that struck-by accidents, along with falls from elevation and caught-in/between accidents, accounted for 75% of total workplace injuries. Struck-by injuries occur when a person forcibly comes into contact with an object or equipment, whether due to a flying, falling, swinging, or rolling object (OSHA, 2021). Chi et al. (2019) found that a majority of struck-by accidents in construction were linked to environmental risk factors such as flying objects, overhead moving or falling objects, and material handling equipment/methods, as well as human factors like misjudgment of hazardous situations. To address such risks, OSHA recommends that construction workers maintain a safe distance from heavy equipment during operation and remain aware of its location at all times. However, construction sites often necessitate proximity between workers and equipment, posing a significant safety challenge (Teizer, 2019; Pradhananga & Teizer, 2019). In these scenarios, adhering solely to OSHA guidelines may not suffice.

For construction project managers, this highlights the importance of controlling safety procedures, conducting compliance checks, ensuring worker adherence to health and safety measures, and enforcing guidelines to limit exposure to occupational hazards (Karakhan & Gambatese, 2018). Traditionally, safety management involves training workers to be aware of potential risks associated with their tasks and rely on their skills and experience to handle identified and unidentified hazards. However, workers' ability to navigate hazardous situations is influenced by various factors, including their awareness of safety, motivation, time pressure, and peer pressure (Guo et al., 2017; Reed et al, 2022).

Both hitherto and recent research emphasize the significance of implementing safety controls to prevent fatalities and injuries in construction (Alomari et al, 2018). The construction industry's complexity, characterized by a diverse range of activities, increases the exposure to hazards and health and safety issues (Khan et al, 2019). This heightened risk stems from working with heavy machinery, operating from elevated platforms, and facing hazardous conditions and weather, all of which can result in injuries, accidents, and near misses (Mohammadi et al., 2018). Consequently, safety management has become a critical area of concern, particularly within the construction sector. Safety management involves overseeing safety regulations, practices, and principles in day-to-day operations on construction sites (Abas et al, 2020). Literature on safety management divides the process into two key stages: pre-construction and during construction (Zhang et al, 2013; Pan et al, 2020). Pre-construction safety planning aims to minimize hazardous exposures during the construction project (Guo et al, 2017), transitioning into safety management during the construction process itself. This involves utilizing appropriate technologies to minimize injuries and repetitive tasks, managing health and safety, and implementing hazard identification processes to mitigate risk events (Pan et al, 2019).

This entails providing workers with training on safety culture, practices, and behaviour, along with ensuring compliance with regulations to prevent workplace injuries (Eiris et al, 2018). Numerous studies have been conducted to identify and assess factors contributing to poor health and safety management practices and causing accidents and injuries. Ismail et al. (2012) observed an association between workers' behaviour and their safety on site, suggesting that safety-conscious and compliant workers are at lower risk of accidents and injuries. Similarly, Williams et al. (2019) highlighted the significance of safety culture as a critical success factor in preventing construction injuries, a finding supported by Gao et al. (2018) and Hamid et al. (2019), who emphasized the link between organizational attitude and the implementation of safety practices in impacting injury outcomes. While there is consensus in the literature regarding the potential of construction technologies in preventing injuries and fatalities in the UK (Pan et al, 2020; Gleeds et al, 2021; Green et al, 2018), ongoing research and implementation are essential to continuously improve safety outcomes in the construction industry.

4.6 Application of Technologies for Safety in Construction

Several cutting-edge technologies are currently revolutionizing safety measures within the construction industry. These emerging technologies offer a more comprehensive understanding of construction environments by integrating data triangulation, assessment, and informed analysis, surpassing the capabilities of traditional construction methods. Among these technologies is the Internet of Things, which leverages various sensors to monitor workspaces and assess hazardous conditions, enabling proactive safety measures (Wang & Liu., 2022). Additionally, wearable technologies equipped with diverse sensors, affixed to clothing and equipment, including body-worn devices, enhance on-site monitoring capabilities, prevent falls, identify hazard zones, and provide real-time proximity detection and warning systems to mitigate risks (Awolusi et al., 2018; Cheng et al., 2023).

Research by Wu et al. (2022) underscores how the development of sensing technologies has transformed construction safety practices. However, they also highlight challenges associated with these technologies, such as the risk of signal blockage and attenuation, which can complicate asset and personnel positioning and monitoring (Cheng et al., 2021). Moreover, it is essential to recognize that these technologies are not universally applicable to all construction challenges. Nonetheless, they offer a fresh perspective on construction safety practices and have the potential to enhance safety monitoring quality compared to traditional methods.

Recent advancements in robotics have revolutionized safety measures in the construction industry, particularly in preventing injuries resulting from working in tight or outdoor spaces where collision risks are high (Yoshida, 2019). One such development involves the integration of robotics with an active transponder system. These robots serve a dual purpose: firstly, they act as proximity alarms, alerting humans to take precautionary measures to reduce the risk of accidents and near misses, especially in assessing the proximity of workers and equipment movements. Additionally, they trigger vibro-tactile warning systems when hazardous incidents are imminent. Moreover, these robots have additional utility in transmitting real-time work data, situational information, and positioning details to a centralized database. This data enables the generation of safety reports, ensuring ongoing safety compliance and risk management (Chan et al., 2020). However, studies (Greenwood et al, 2019; Rashid et al, 20202) suggest that the effectiveness of these robots depends on various factors, including size, specifications, range of functionalities, adaptability, and positioning accuracy. Challenges such as metal interference and errors or data loss due to wireless connectivity issues with the server and sensors also impact their efficacy.

4.6 Health and Safety Regulations in the UK construction industry

In the UK, the Health and Safety at Work Act (HASAWA) 1974 and the Management of Health and Safety at Work Regulations 1999 constitute the primary legislation governing workplace health and safety (Anagha & Xavier, 2020). The HASAWA aims to ensure that employers uphold safe working environments as a fundamental practice, while the Management Regs impose a duty on employers to assess and manage risks, implement measures to mitigate risks, and establish health and safety policies in the workplace. Despite the comprehensive framework provided by these laws, there is currently a lack of specific regulations addressing the use of robotics and emerging technologies in the UK workplace. While existing legislation offers a broad safety net for worker protection concerning machinery use, regulations specifically tailored to AI robots are absent. These legislations serve as the cornerstone for addressing health and safety concerns across various industries in the UK, encompassing manufacturing, construction, agriculture, and services.

In the UK construction industry, the safety of workers is governed by several frameworks of laws and regulations, including the Health and Safety at Work etc. Act 1974, which mandates employers to maintain a safe work environment and take reasonable precautions to prevent accidents and injuries, alongside various regulations tailored to specific aspects of construction work such as the Construction (Design and Management) Regulations 2015 (CDM) that outline requirements for managing health and safety in construction projects, the Work at Height Regulations 2005 which establish guidelines for working at elevated heights, the Manual Handling Operations Regulations 1992 governing the safe handling of loads, the Provision and Use of Work Equipment Regulations 1998 prescribing safety measures for using workplace equipment, the Personal Protective Equipment at Work Regulations 1992 mandating the provision and use of personal protective gear, the Control of Substances Hazardous to Health Regulations 2002 regulating the handling of hazardous substances, the Reporting of Injuries, Diseases and Dangerous Occurrences Regulations 2013 (RIDDOR) compelling employers to report certain accidents and incidents to the Health and Safety Executive, and the Health and Safety (Display Screen Equipment) Regulations 1992 ensuring the protection of workers using display screen equipment, with adherence to these regulations being mandatory for all employers in the UK construction industry to ensure the safety and well-being of workers (Kaur et al, 2019).

The CDM Regulations of 2015, replacing the CDM 2007, provide guidance on the legal requirements applicable to the whole construction process – from initiation to completion

(CDM, 2015). The Construction (Design and Management) Regulations 2015 (CDM 2015) are a set of regulations in the United Kingdom that set out legal duties for managing and controlling construction projects to ensure the health and safety of all those involved in the construction process. These regulations, applicable to all construction projects, including high-risk ones, establish legal duties aimed at managing and controlling construction projects to safeguard the health and safety of all involved parties. They mandate continuous focus on project health and safety, enhanced planning and management, hazard identification, and diligent adherence to health and safety standards throughout the project lifecycle (Beardsley, 2015).

Essentially, CDM aims to ensure contractors' compliance with project plans and the execution of projects in a manner that prioritizes health and safety, necessitating prudent planning, appropriate skills, clear communication, and engagement with workers (CDM, 2015). Effective application of CDM principles, particularly during planning and implementation stages, has been shown to enhance risk assessment, safety planning, and hazard elimination in construction works (Eiris et al, 2018). Moreover, CDM serves as a mitigation strategy against health issues on construction sites while enhancing safety planning and overall performance (Bansal, 2011). By delineating roles and responsibilities in health and safety management, CDM fosters an integrated approach among stakeholders in the UK construction sector, particularly in project design, planning, and execution.

The Construction (Design and Management) Regulations 2015 (CDM 2015) encompass a comprehensive set of rules applicable to all construction undertakings in the UK, irrespective of their scale or duration, including those categorized as high risk. CDM 2015 is primarily designed to ensure meticulous management of health and safety throughout the construction lifecycle. High-risk projects, characterized by elevated levels of danger or potential harm to workers and others, encompass tall buildings, hazardous material involvement, or projects of intricate complexity. Duty holders for high-risk projects under CDM 2015 bear additional responsibilities to effectively manage and mitigate health and safety risks inherent in the project. These responsibilities entail comprehensive planning, organization, and monitoring to identify and control all associated risks, ensuring the implementation of requisite safety measures to safeguard workers and stakeholders. While CDM 2015 regulations are universally applicable to construction activities, irrespective of their dimensions, they entail heightened requirements for high-risk projects, defined by their propensity for significant risk exposure, such as tasks involving elevated work, excavation, or hazardous substance handling.

Some of the key requirements of CDM 2015 for high-risk construction projects include:

i. Appointment of a Principal Contractor: The client is responsible for appointing a principal contractor to plan, manage, and coordinate the construction work.

ii. Preparation of a Health and Safety Plan: A health and safety plan must be prepared before construction work begins, outlining how the risks associated with the project will be managed and controlled.

iii. Notification to the Health and Safety Executive: The client is required to notify HSE of the project before construction work begins, and to provide information about the project, the client, the principal contractor, and the designer.

IV. Pre-construction Information: The client is required to provide designers and contractors with pre-construction information, including any known risks or hazards associated with the project.

v. Management of Construction Work: The principal contractor must manage and coordinate the construction work to ensure that all risks are identified and controlled, and that the necessary safety measures are in place.

vi. Provision of welfare facilities: The client, designer, and principal contractor must provide welfare facilities, such as toilets, washing facilities, and canteen facilities, for the use of the workers on the construction site.

vii. Communication and Coordination: The client, designer, and principal contractor must communicate and coordinate with each other to ensure that the project is safe and that the risks are managed and controlled.

viii. Regular Inspection: The client, designer, and principal contractor must ensure that regular inspections are carried out to ensure that the construction work is being carried out safely.

ix. Handling and Disposal of Waste: The client, designer, and principal contractor must ensure that waste is handled and disposed of safely and by environmental regulations.

x. Emergency Arrangements: The client, designer, and principal contractor must have emergency arrangements in place in case of an emergency.

The Manual Handling Operations Regulations 2002 (MHOR) mandate employers to oversee compliance with manual handling regulations, placing primary responsibility on them to ensure adherence. These regulations encompass various manual handling activities in the workplace and aim to safeguard the health and safety of all involved. Employers are obligated to provide comprehensive training on handling techniques, furnish appropriate equipment suitable for the task, and maintain such equipment properly. MHOR applies universally to manual handling activities, encompassing those deemed high risk, such as lifting heavy loads, executing repetitive or awkward movements, or working in confined spaces, especially prevalent in construction sites.

Under the MHOR, employers have a legal duty to assess and manage the risks associated with manual handling activities and to take steps to prevent or control those risks.
Employers are required to:

i. Assess the risks of manual handling activities and take steps to prevent or control those risks.
ii. Provide information and training to employees on safe manual handling techniques.
iii. Provide employees with appropriate handling equipment and ensure it is properly maintained.
iv. Provide employees with regular health and safety supervision.
v. Make sure that the working environment is safe and healthy, and that it is suitable for the manual handling activities that are carried out.
vi. Employers should also consider providing mechanical aids and other equipment to help employees with manual handling tasks, and redesigning tasks or workstations to reduce the risk of injury.
vii. Employees also have a responsibility to follow the safe manual handling procedures that have been put in place, and to use any equipment provided. If an employee is aware of a manual handling risk, they must report it to their employer immediately.

The RIDDOR 1995 is a requirement that employers record and report all accidents and injuries at the workplace, from near misses to repetitive strain injury, carpal tunnel syndrome, tendonitis, occupational dermatitis, including the failure or collapse of lifting equipment. This regulation further covers all activities relating to manual handling in the UK and ensures that workers comply with its regulatory requirements (Greene et al, 2019). The regulation requires that construction project managers provide detailed information for training on equipment use, manual handling processes, and report near misses and accidents, and injuries at the construction site.

4.8 Chapter summary

This chapter was an in-depth exploration of robotics and its uptake in the UK. This was assessed against the backdrop of existing regulations and the factors currently impeding the uptake of its technology despite evidence pointing to the utility of its technology. Furthermore, an investigation of injuries in the UK was identified and discussed to ascertain the prospect of applying robotics and automation as a preventive innovative intervention to reduce its incidence. This chapter delved into the prevailing health and safety standards concerning robotics, offering a critical lens through which to evaluate their relevance within the construction sector in the UK. By scrutinizing these standards, the analysis gained valuable insights into how they intersect with the industry's efforts to mitigate construction-related injuries and enhance overall health and safety protocols. Moreover, it shed light on the extent of their applicability and identified any inherent limitations within the regulatory framework.

This chapter provided a comprehensive examination of robotics uptake within the UK construction sector. It assessed this against the backdrop of existing regulations and the prevailing factors hindering the technology's adoption, despite evidence showcasing its utility. Moreover, it investigated UK injury trends, aiming to assess the potential of robotics and automation as innovative preventive measures to mitigate such incidents. The findings revealed a deficiency in clear regulations and legislations incentivizing robotic technology adoption for injury prevention in the UK. Furthermore, there was a lack of evident government strategies outlining plans for encouraging robotic adoption, especially tailored to the construction industry. Even where such plans existed, they often lacked specificity regarding stakeholder involvement in the construction sector. These glaring gaps necessitate further exploration and emphasize the importance of delving into stakeholders' views within the UK construction industry to elucidate how these technologies can be effectively utilized for injury prevention. Neither is there an evident roadmap detailing how the government intends to achieve some of its blueprint targeted to encourage robotic adoption.

As stated, existing strategies are not specifically tailored to the construction industry, and there is limited bandwidth to ascertain the degree to which stakeholders (in the construction industry in the UK) were incorporated in the process. These yawning gaps leave room for further exploration and underscore the need for an in-depth analysis of the views/perceptions of stakeholders in the UK construction industry on how these technologies can be utilised in the prevention of injuries and in articulating a roadmap for their adoption.

CHAPTER FIVE: Research Methodology

5.0 Introduction

The research method is a crucial component of the research process, encompassing the research design and the methodology used to gather, analyse, and validate data for studying the uptake of robotics in preventing construction-related injuries in the UK. The methodological approach adopted is closely aligned with the research objectives and rationale, providing the analytical framework for operationalizing research variables and addressing key research questions. Given the significance of this thesis topic, selecting the appropriate approach and research design is essential for systematically establishing evidence. This chapter is organized into five main parts. First, it delves into the research design and outlines the rationale behind its selection. Next, it explores the research approach employed and its relevance to the overall research process. Finally, the chapter addresses ethical considerations inherent in the research, ensuring that ethical principles guide the conduct of the study and safeguard the interests of all stakeholders involved. Each section of this chapter contributes to establishing a robust foundation for conducting the research and interpreting its findings effectively.

5.1 Research Onion

The research methodology was crafted using the research onion model developed by Saunders et al. (2012), which serves as a framework for aligning the researcher's beliefs and philosophical assumptions with the research questions and chosen methodology. This model conceptualizes the research process as a layered structure, akin to the layers of an onion, each contributing to the holistic understanding of the research process.

However, although the model itself was initially tailored for business studies and thus necessitates some adaptation for application in the field of construction engineering, it is important to highlight its suitability in elucidating the research process. This is primarily because of the nature of the data collection process, which mandates the gathering and analysis of empirical data from respondents to address the research objectives underlying the rationale for its adoption (Saunders et al., 2019). As noted by Silverman (2012:124), there is no one-size-fits-all approach to comprehending research phenomena; however, employing an appropriate model furnishes the empirical foundation necessary to achieve diverse research objectives. However, the model's suitability to the research process lies in its ability to articulate the research design in a way that serves as the anchor elucidating the various stages, approaches, and rationale behind the different techniques employed throughout the research. Essentially, it functions as a map that guides the research action (Thornwell, 2009).

The metaphor of the onion reflects the idea that the research process comprises distinct layers, each with its unique role, yet collectively forming a cohesive whole. At the core of the onion lies data collection and analysis, representing the central focus of the research process. Saunders et al. (2019) delineate six layers within the research onion: philosophies, approaches, strategies, choices, time horizons, and procedures. These layers encapsulate various aspects of the research process, from overarching philosophical perspectives to practical methodological considerations, guiding the researcher through the systematic exploration and analysis of the research topic. At the heart of the research onion lies the critical phase of data collection and analysis, encompassing the methods employed to gather primary or secondary data essential for addressing the research questions. The subsequent layer pertains to the time horizon, which delineates the timeframe necessary for completing the research. The temporal dimension of research is crucial to ensure feasibility and practicality within a defined timeframe.

A cross-sectional approach entails a predetermined timeframe for data collection, contrasting with longitudinal studies where data collection extends over an extended period to capture changes over time and ensure the validity and reliability of the data (Thornbell, 2013). This parallels stochastic modelling, where the likelihood of various outcomes is assessed using random variables to predict future scenarios. In the context of this research, the nature aligns more closely with cross-sectional data due to the need for empirical data collection within a specific timeframe (Biggam, 2003). This approach facilitates the examination of hypotheses regarding the usability of data and enables the synthesis of findings to address the research objectives effectively.

The third innermost layer of the research onion pertains to research choices, delineating the extent to which the data collection process aligns with qualitative, quantitative, or mixed methods to address research questions and fulfil core research objectives (Morecambie, 2017). The nature of the research plays a pivotal role in determining these choices, often embedded within the research objectives that serve as the analytical cornerstone for the thesis.

It is salient to recognize that research choices oscillate among these three options. As Silverman (2012) observes, if the research aims to establish factual information regarding the topic, quantitative research is more suitable. Conversely, qualitative research is preferable if the objective is to explore and gain deeper insights into real-world problems (Tenny, 2022). Moreover, quantitative research offers a structured approach for data organization and interpretation, while qualitative research preserves the richness and individuality of responses, enabling a more nuanced understanding of the phenomena under investigation. In the case of mixed methods, it involves a combination of both quantitative and qualitative approaches. The study embraced a mixed method of data analysis to explore and analyse the nexus between robotic adoption and its efficacy in preventing construction injuries in the UK, as elaborated in the subsequent paragraphs.

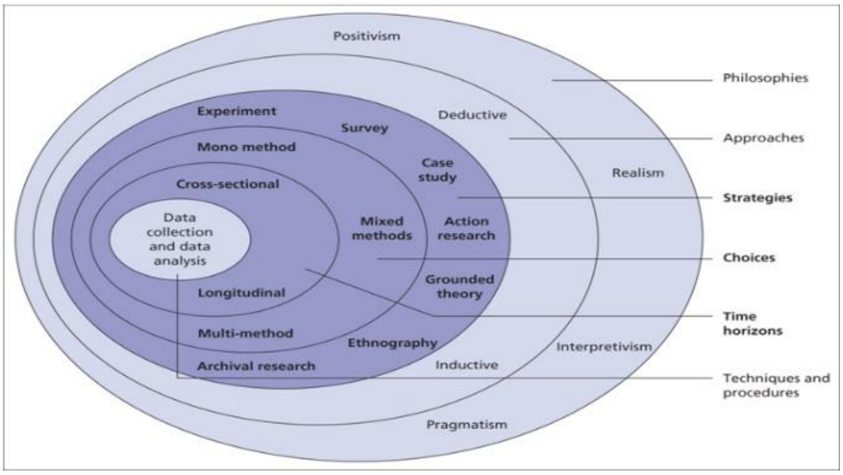

Figure 11: Research Onion. Saunders et al (2019)

The fourth layer of the research onion delves into research strategies, as outlined by Saunders in her model, which categorizes this into four key components: survey, case study, action research, grounded theory, and ethnography research strategies. The research strategy functions as the action plan guiding the implementation of the research process, which is pivotal for attaining research objectives (Biggam, 2003). It offers clarity on how research questions are addressed in the data collection phase, facilitating data organization, synthesis, and communication of research findings (Donnenfield et al, 2018). Recent studies have introduced narrative inquiry as another component of the research strategy (Tulum et al, 2020). Given the impossibility of adopting all research strategies, the study opted for the survey approach as it presented the most suitable option for gathering empirical data essential to the research process, aligning with the chosen research choice (Reece et al, 2021). The rationale is further elaborated in the subsequent paragraphs.

In the second outermost layer, the research approaches are essentially divided into two types: inductive and deductive. An important distinction between the two lies in their fundamental orientations. The inductive approach revolves around observation and theory formulation, which are then used to synthesize empirical findings after the research, thereby addressing the research question (Finlar et al., 2015). Conversely, the deductive approach prioritizes the development of theory from existing theories, progressing from specific observations rooted in prior research to broader generalizations—the opposite trajectory of the inductive approach (Saunders et al., 2019).

The outermost layer, research philosophy, essentially encapsulates the beliefs guiding how data should be gathered, analysed, synthesized, and utilized, rooted in overarching research assumptions, beliefs, values, and motivations. This will be discussed in greater detail in the following paragraph.

Next, we delve into the layers of the research onion model and apply it to the research process, specifically examining its relevance in exploring the relationship between robotic adoption and its role in preventing construction-related injuries. Metaphorically peeling back the layers of the onion provides clarity on the myriad factors influencing research decisions and how they have been utilized and contextualized to address the research objectives.

5.2 Research Philosophy

The research philosophy, as its name suggests, offers an analytical lens through which the synthesis of research is understood, shaped by various beliefs, assumptions, and values guiding the research process (Bell et al., 2012). Research methods are not chosen arbitrarily; they are justified based on a set of reasons that explain why a particular approach was favored over others (Lowe et al., 2018). Within the research onion model, three distinct research philosophies emerge: positivism, interpretivism, and pragmatism (Saunders et al., 2019). Interpretivism, for instance, contextualizes research within a sociological framework, focusing on actions and events influenced by societal norms and values (Lin et al., 2018). It privileges subjectivity over objectivity, relying on values and beliefs to interpret research truths that may not be systematized or generalized (Maihu et al., 2019). However, this subjectivity renders it unsuitable for the current research. As the aim is to gather empirical data, the quality of this data must allow for synthesis and analysis to ensure validity and reliability in addressing the research agenda.

Pragmatism, within the realm of epistemology, is rooted in the idea that research should move away from abstract concepts and aim for an objective reality grounded in practical understanding of real-world issues (Patton, 2005:153). It operates on the premise that data is socially constructed (Kelly & Codeiro, 2020). However, pragmatism aligns more with an interpretivist interpretation of social reality, making it compatible with subjectivity in an ontological sense, particularly because research data often reflects values and meanings that are not value-free for the researcher (Morgan, 2014). One core tenet of pragmatism is that all research should generate useful and actionable knowledge that addresses real-world problems or redefines ways of understanding objective reality through the interconnectedness of experience, knowledge, and action (Feiler, 2010). Despite its meaningful implications in addressing objectives related to robot adoption and developing a roadmap for implementation solutions, the subjectivity inherent in data collection renders pragmatism an incompatible underlying research philosophy for this study, which requires a focus on objective data.

The positivist research philosophy operates on the premise of conducting research grounded in measurement and reason, aiming for knowledge that is neutral and quantifiable through observation or action. It emphasizes that research phenomena must be measurable to achieve certainty (Silverman et al., 2012). Positivism rejects subjectivity and bias, favoring an epistemology rooted in empiricism, quantification, and analysis, which allows for the synthesis of research findings into systematic and generalizable conclusions (Maihu et al., 2019). By aiming to uncover research facts through objective assessment of collected data, positivism provides a framework for systematic exploration (Bell et al., 2012).

Interpretivism and realism are deemed unsuitable for this research basis due to their subjective and non-objective epistemological and ontological perspectives on data collection (Saunders et al., 2019). In contrast, the positivist research philosophy is well-suited for exploring the intersection between robotics and its role in injury prevention. It aligns with the belief that reality can be objectively studied, advocating for systematic observation, hypothesis testing, and generalization based on key findings (Silverman et al., 2012). This approach mirrors the deductive method, which progresses from specific research data to generalizations derived from research outcomes (Park et al., 2020).

Given that the positivist stance aligns with the objective of this research, which involves a thorough and objective assessment of evidence to synthesize findings regarding how robotics intersects with the prevention of construction-related injuries, the positivist philosophy serves as the foundational philosophical approach for this thesis. This philosophical stance does not imply that the thesis is purely philosophical or solely concerned with theoretical issues; rather, it signifies the researcher's intention to adopt a positivist approach rooted in objectivity, value-neutrality, and scientific quantifiability to conclude this research (Silverman, 2015). The positivist research philosophy asserts that the most effective way to comprehend a phenomenon is through systematic observation and hypothesis testing using quantitative methods, such as surveys. Surveys enable the collection of substantial data from diverse participants, offering valuable insights into industry trends, current adoption rates of robotics, and the challenges hindering implementation.

5.3 Research Approach

The research approach chosen for investigating the relationship between robotics innovation adoption and the prevention of construction injuries is the deductive approach. In contrast to the inductive approach, which seeks patterns from empirical observations to generate new theories, the deductive approach tests existing theories using collected data to draw research conclusions (Lin et al., 2018). The scope of the deductive approach extends beyond theoretical exploration to include the assessment of empirical data gathered during the research process. It focuses on making approximations and deriving research conclusions and generalizations from synthesized findings (Coleman et al., 2012). Given the nature of this research, which aims to understand the perception of key construction stakeholders regarding robotics adoption and use this knowledge to draw systematic conclusions about its utility in preventing construction injuries, the deductive approach is considered the most suitable and therefore the rationale for its adoption.

The rationale for adopting the deductive approach is rooted in its alignment with the nature of this research. As elucidated earlier, this methodological choice resonates with the positivist philosophy, which prioritizes objectivity. Consequently, the research aims not to generate new theories but to test existing research phenomena and derive conclusions (Marouf et al., 2018). The deductive approach provides a structured framework for assessing how these existing phenomena align with the research objectives, facilitating the drawing of research conclusions. This alignment with a quantitative approach is evident, as it follows an objective analytical framework consistent with the research onion model.

5.4 Research Choice

The primary objective of selecting a research approach is to establish factual information regarding the subject and topic under investigation, ensuring alignment with the research aim. The choice of research methodology is crucial as it significantly influences the success and overall quality of the research study and its documentation. Moreover, a well-chosen methodology facilitates the exploration of interconnections between the variables under scrutiny, allowing for an objective analysis of research evidence using appropriate statistical tools to establish stochastic relationships between phenomena (Lester, 2020). It is widely acknowledged that a clearly defined research question is fundamental to the execution of a successful research strategy (Maartens et al., 2020). Among the various research strategies available, the mixed method was deemed most suitable for this research. Bazely (2003) defines the mixed method as the utilization of both numerical and textual data, as well as alternative tools such as statistics and analysis, within the same research framework. This approach involves integrating qualitative and quantitative research paradigms across different phases of the study, enabling a comprehensive exploration of the research topic.

According to Burke et al. (2005), mixed methods research represents a "third wave" or movement beyond paradigm wars, providing a logical and practical alternative. Creswell, Fetters, and Ivankova (2004:7) emphasize that mixed methods research goes beyond merely collecting qualitative and quantitative data; it involves integrating, relating, or mixing data at various stages of the research process. They suggest that the rationale behind mixing methods is that neither qualitative nor quantitative approaches alone are sufficient to capture the intricacies of a situation. When combined, however, they complement each other and offer a more comprehensive analysis. Expanding on this rationale, Johnson and Onwuegbuzi (2004:17) highlight that mixed methods research encompasses induction for discovering patterns, deduction for testing theories and hypotheses, and abduction for uncovering and relying on the most suitable explanations for understanding results.

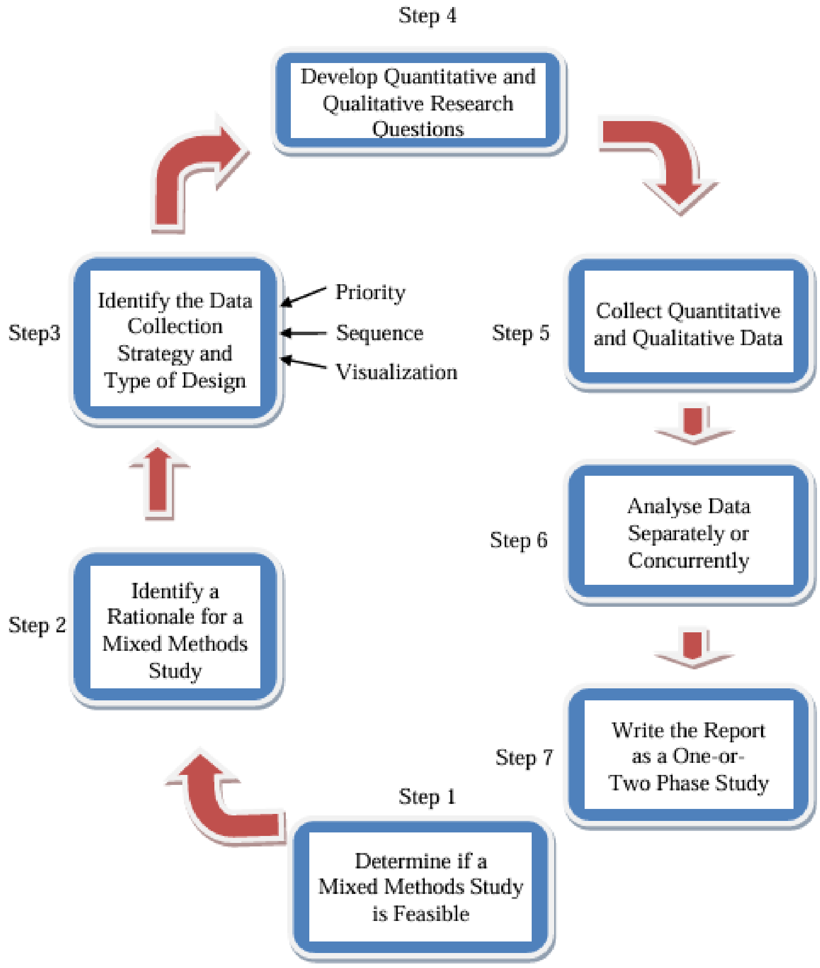

Figure 12: Research Choice loop. Source: Johnson and Onwuegbuzi (2004)

Onwuegbuzie and Leech (2006:479) outline several rationales for integrating qualitative and quantitative approaches, including participant enrichment, instrument fidelity, treatment integrity, and significance enhancement. Participant enrichment involves expanding the participant pool, with Leech (2006) arguing that larger samples yield more reliable and valid research findings. Instrument fidelity focuses on optimizing the appropriateness and utility of research instruments. In this study, questionnaires and interviews were employed as instruments. Treatment integrity pertains to using mixed methods to evaluate the fidelity of interventions or programs, while significance enhancement aims to enrich the researcher's interpretation of data.

5.5 Research strategy

The research strategy delineated how the research was conducted from inception to data collection, collation, analysis, and final systematization. A well-defined and executed research strategy hinged on a clear research question, appropriate sample selection, a reliable and valid questionnaire, and suitable data analysis methods (Maartens et al, 2020).

Among the three research strategies potentially applicable to this research, the quantitative research strategy was deemed most suitable. This choice aligned with the ontological stance of the research philosophy of the dissertation. By employing the quantitative strategy, the research could establish a methodological nexus between the research data and evidence and subject them to quantitative analysis, deducing research conclusions (Miles et al, 2018). This approach facilitated exploring the interconnection between the variables under investigation and objectively considering the research evidence using appropriate statistical tools to establish the stochastic relationship between the phenomena under investigation (Lester, 2020).

The first step in implementing a survey research strategy for robotics in the construction industry was to define the research question and objectives. The research question needed to be specific and focused, such as "What were the current and planned uses of robotics in the construction industry?" and "What were the perceived benefits and challenges of using robotics in construction?" Next, a sample of participants was selected, representative of the construction industry, including professionals from various roles like architects, engineers, contractors, and facility managers. The sample size was chosen to be large enough to provide a robust and reliable dataset. Subsequently, the survey questionnaire was developed and tested for reliability and validity, including questions covering a variety of topics such as current and planned use of robotics in construction, perceived benefits and challenges of using robotics, and opinions on the future of robotics in the industry.

5.6 Survey

In this dissertation, the data collection strategy revolves around the survey method, which falls under the quantitative research strategy. Despite the historically slow uptake of new technologies like robotics in the construction industry, there has been a recent surge of interest in leveraging robots to enhance efficiency and safety at construction sites. Conducting a survey offers an apt approach to gauge the current status of robotics in construction and to pinpoint avenues for future exploration. Surveys, as a research method, entail gathering data from a sample of individuals or organizations via self-administered questionnaires or interviews (Cassidy, 2008). They are advantageous for swiftly amassing substantial data at a relatively low cost. Additionally, their remote administration makes them particularly suitable for studying dispersed populations, such as construction firms. The survey process typically kicks off with identifying the target population. In this study's context, the population would likely encompass construction companies with either prior experience in or a keen interest in adopting robotics for their projects. Sampling methods like random or stratified sampling could be employed to select the survey sample.

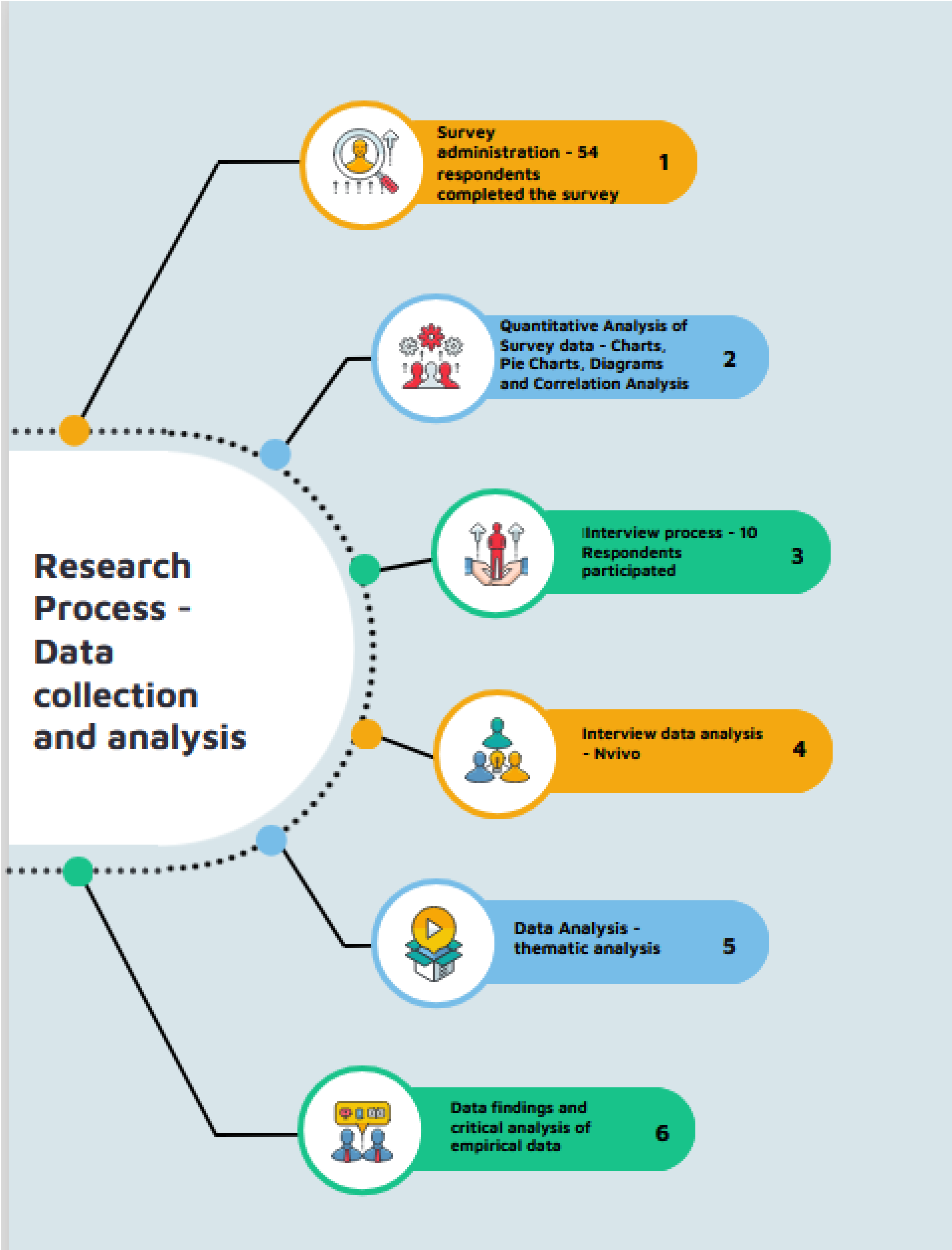

Figure 13: Research Process

The survey design would encompass a blend of closed- and open-ended questions to capture both quantitative and qualitative data. Closed-ended questions, including multiple-choice and Likert scale queries, would delve into aspects such as the types of robotics employed in construction projects, the associated benefits and challenges, and the extent of investment in robotics. Open-ended questions would allow respondents to furnish additional insights and information. Furthermore, the survey would probe into details regarding the company's size, location, and project typology to discern potential influences on robotics adoption. Queries concerning the present status and future trajectory of automation and robotics in construction, as well as prevailing challenges, would also feature in the questionnaire. This survey methodology for robotics in the construction sector entails crafting a comprehensive questionnaire tailored for distribution among professionals in the construction industry. It aims to gather insights across various dimensions, including current and prospective use of robotics, perceived advantages and The survey's participant sample was diverse, reflecting various roles within the construction industry, encompassing architects, engineers, contractors, and facility managers.

Distribution channels for the survey included email, online platforms, and traditional mail. Data analysis involved descriptive statistics like frequencies, percentages, and means to offer an overall snapshot of responses. Additionally, inferential statistics such as chi-squared tests and logistic regression were used to uncover patterns and correlations among variables. The survey findings offered valuable insights into the then-current status of robotics in construction, pinpointing areas necessitating further research. Moreover, these insights guided the development of robotics technology and policies supporting its integration. Once data collection concluded, appropriate statistical techniques were applied to unveil patterns and trends, culminating in a comprehensive report featuring both quantitative and qualitative data. This report was instrumental in understanding the then-present landscape of robotics in construction, shedding light on future research opportunities, and enlightening the industry about the advantages and hurdles of employing robotics. The survey served as a cost-effective and streamlined approach to gathering insights from a dispersed population, delivering a rich blend of quantitative and qualitative data on obstacles and outlooks on the future role of robotics in construction.

Through the survey, the researcher obtained vital primary data from the research participants. Existing literature classified survey instruments into three types based on their structure – structured, semi-structured, and unstructured (Silverman, 2015). Although this dissertation did not delve into an exploratory analysis of these types, it utilized the semi-structured questionnaire for its research purposes (Raskind et al., 2019). The semi-structured questionnaire comprised both open and structured questions, affording participants greater flexibility to share insights and knowledge in response to the survey questions. As noted by Saunders et al. (2012), such surveys are valuable as they can capture perspectives that may not have been addressed in the questionnaire (Miles et al., 2018).

Additionally, the psychometric scale of preferences forming the basis of survey questions proved particularly useful for quantifying and analysing the data (Lowe et al., 2018). Other sources of data for this dissertation were evaluated in the empirical literature review section.

5.7 Sampling population and procedure

Considering the impracticality of aggregating the entire population of construction stakeholders and practitioners in the United Kingdom, sampling was deemed crucial for this research. The selected sampling population was deemed adequate for this study, given the higher likelihood of having participants with the technical expertise and extensive knowledge necessary to address the research questions effectively. Therefore, a purposive or judgmental sampling approach was employed for this research investigation. This method, also known as authoritative sampling, involves the researcher selecting participants based on their judgment of their knowledge and professional experience (Cresswell, 2003). As this procedure relies on the researcher's judgment rather than random selection, it is non-probabilistic (Silverman, 2015).

To explore the utilization and potential of robotics in construction, it was imperative to employ a sampling procedure that accurately represents the population of interest. A representative sample mirrors the characteristics of the population under study (Res et al, 2017). In investigating robotics in the construction industry, the population of interest encompasses various construction professionals, including architects, engineers, and contractors. The sampling procedure for survey research on robotics in construction entails several key steps. Firstly, defining the population of interest is essential, focusing on construction professionals in this scenario. Subsequently, selecting an appropriate sampling method becomes paramount. The two primary sampling methods are probability sampling and non-probability sampling (Saunders et al, 2012). Probability sampling involves randomly selecting samples from the population, utilizing methods such as simple random sampling, stratified random sampling, or cluster sampling (Hall et al, 2020). Simple random sampling, the most fundamental probability sampling technique, entails randomly selecting samples from the entire population (Biggam, 2015). Stratified random sampling divides the population into subgroups (strata) and selects samples from each stratum. Cluster sampling involves dividing the population into clusters, then selecting clusters randomly, followed by sampling individuals from each selected cluster (Silverman, 2015).

Non-probability sampling, conversely, relied on the researcher's judgment or convenience in selecting samples (Orth et al, 2019). Convenience sampling was the most prevalent non-probability sampling method. Once the sampling method was determined, establishing an appropriate sample size became crucial. The sample size had to be sufficient to yield a comprehensive and dependable dataset. The sample of participants needed to mirror the diversity of roles within the construction industry, encompassing architects, engineers, contractors, and facility managers. Implementing a robust sampling procedure for survey research on robotics in construction was pivotal to ensuring the sample accurately represented the population of interest. This procedure necessitated selecting an appropriate sampling method, whether probability sampling or non-probability sampling, and determining a sample size that guaranteed a robust and dependable dataset. The participants selected had to offer a representative cross-section of the construction industry, spanning various roles such as architects, engineers, and contractors.

5.8 Semi-structured interview

The semi-structured interview method is one of three primary approaches used to gather credible and insightful research data through in-depth examination of both people and topics (Biggam, 2008). The other two interview types are structured and open interviews. Structured interviews are rigidly designed, allowing minimal room for questions outside the predetermined data collection framework. This format is typically employed when research necessitates direct and specific views crucial to informing the research activity (Bollock, 2018). In contrast, the semi-structured interview process offers more flexibility for discussion, exploration of issues, and deeper inquiry while maintaining a formal tone and dynamic flexibility. This ensures that respondents' perspectives remain aligned with the research scope without straying too far off course (Ruth et al., 2018).

The choice of interview approach typically depends on the scope and nature of the research design and the type of data the researcher aims to gather regarding the research topic (Bryman, 2011). Unlike structured interviews, open interviews have no defined structure and can easily veer off-topic. As described by Gibson et al. (2019), they are akin to fishing in open waters, where the conversation follows whatever topic is "hooked," making them unsuitable for rigorous research processes and designs. Although it allows for opening the questionnaire and facilitating the inflow of unstructured information that is always relevant for interviews (Silverman, 2010). In contrast, the semi-structured interview process allows researchers to capture respondents' overarching viewpoints while also providing latitude to delve deeper for additional information. This approach is credited with yielding richer and more insightful accounts compared to structured research instruments (Caldwell, 2016). It also offers researchers greater flexibility in probing core themes emerging from discussions and facilitates the integration of respondents' experiences to provide a more comprehensive account interpretable by the researcher. As noted by Silverman (2010), the semi-structured interview process enables researchers to pose questions sequentially to interviewees, experts, or respondents based on a predetermined sequence.

5.8.1 The semi-structured interview process

The process followed for the semi-structured interviews was meticulously designed. Initially, the literature acted as a guide, shaping the scope and framing the questions crucial for informing the interview process. This ensured that the interview questionnaire encompassed the key themes essential to answering the research questions. The introductory section of the questionnaire served to acquaint respondents with the purpose of the interview, elucidating why the research was being conducted and stressing the significance of their feedback. Moreover, this section reassured participants of the utmost confidentiality of the interview and their right to withdraw from the research at any point. Subsequently, consent was obtained to record the interview, with formal verbal confirmation preceding the commencement of the interview process. The interviewer then proceeded with the interview, recording it for subsequent transcription as part of the research procedure.

The initial segment of the questionnaire consisted of open-ended inquiries aimed at gathering information from respondents regarding their years of experience in the construction industry, their areas of specialization, and their general knowledge about robotics. Additionally, respondents were encouraged to pose any follow-up questions they had regarding how the interview data would be utilized to inform the research upon completion. The primary section of the interview comprised seven main questions, each addressing different aspects of the research concerning the utilization of robotics and its intersection with improving health and safety in the UK construction industry. This included factors influencing its adoption and the potential for expanded use of robotics beyond current capacities. To validate the research instrument, pilot testing was conducted with researchers at the University of Salford and two volunteer organizations (small construction companies). The interview schedule was set for 30 to 45 minutes to allow for a comprehensive exchange, and the interview questions are provided in Appendix II.

The researcher implemented several measures to ensure that the interview remained conversational, informative, and guided, preventing respondents from veering off-topic. As Creswell (2008) emphasizes, during interviews, researchers must be mindful of the participants' sensitivities and knowledge levels, understanding how the interview may influence their responses. This entails noting body language cues, avoiding bias in follow-up questions, and ensuring that the interview remains focused on its original design intent. However, as noted by Silverman (2010), it was equally important for the researcher to probe into the feedback provided, guided by appropriate questioning techniques. This ensured that the interview process remained interactive, with the interviewer actively listening, demonstrating interest, and responding in a manner that engaged the interviewee effectively.

In terms of the environment, since the interviews were conducted virtually, the researcher focused on optimizing the virtual setting. This involved ensuring clear visual images and effective internet connections. Additionally, measures were taken to ensure that the recording medium was functioning properly, as tested during the pilot phase, to minimize the risk of data loss. Clear voice recordings were prioritized to facilitate transcription and further analysis at a later stage. On average, interviews lasted 35 minutes, with the longest interview lasting 43 minutes. To enhance data triangulation, as discussed earlier, other data sources were utilized in this chapter to enrich the depth of the interview analysis.

5.9 Techniques for ensuring the trustworthiness of the qualitative research process

Several processes in the literature have been validated for ensuring that qualitative findings measure what they purport to measure and align with best research practices. One of the strategies adopted in this research to ensure data trustworthiness is triangulation. Triangulation involves corroborating, validating, and authenticating data sources using different types of data and methods of data collection (Creswell, 2007). In this study, triangulation was crucial to ensure that the respondents and the data obtained from them were of high quality, meeting criteria that eliminate bias and mitigate prejudices in the research process (Fusch et al., 2018).

To triangulate is to ensure the consistency of research findings across different techniques, samples, and perspectives used to interpret the data (Patton, 1999). Given that this research employs a mixed-method approach enriched by diverse data sources, triangulation was deemed most appropriate for this study. As Creswell (2008) notes, this type of triangulation allows for an extensive data collection process that aligns with mixed methodologies, encompassing both qualitative and quantitative data sources. Using this process, the researcher categorizes the data to ascertain its suitability and appropriateness. This is followed by an extrapolation process to ensure alignment with the study objectives. Consistency in the results indicates trustworthiness in the findings.

Using multiple data sources as a form of triangulation involves comparing and cross-checking data from different perspectives (Merriam, 2009). This process yields significant benefits for research. First, it enables an iterative process that corroborates data comparisons, enhancing the analysis of the research phenomenon. Second, the combination of diverse data sources deepens the understanding of the context surrounding the variables. Finally, through the instrumentation of convergence, it aligns secondary and primary sources of evidence to extrapolate key research findings (Carter et al., 2014).

5.9.1 Respondent validation

To ensure the trustworthiness of the data collected and minimize the risk of misinterpretation or bias, it was crucial to validate the respondents. This validation process aimed to meet the credibility criteria essential for research, ensuring that participants possessed relevant knowledge of the subject matter and were trustworthy (Johnson & Christensen, 2014). Pilot instruments were instrumental in this regard, allowing for the assessment of respondent insights and the suitability of the sample frame. For example, responses from individuals outside the construction industry in the pilot phase were deemed invalid due to their lack of expertise and experience, thus not contributing valid data for the research. This approach aligns closely with Maxwell's findings (2013), emphasizing that the credibility of survey instruments hinges on ensuring that knowledge aligns with experience to yield valid insights informing research findings.

5.10 Qualitative Data Analysis

Several reasons justify the use of qualitative data analysis for synthesizing the evidence necessary to fulfill the research objectives and questions that guided this study. The interview process required a qualitative content analysis method, which aligns with qualitative research focused on analysing text documents from narrative responses, including open-ended surveys and interviews. The main goal is to triangulate and synthesize information to provide answers to the framed research questions (Shannon et al., 2021). Additionally, content analysis is replicable and allows for valid inferences applicable to the context in which they are used, both in quantitative and qualitative research (Biggams et al., 2021).

Besides, it is a method for systematic and objective analysis, making inferences from verbal, visual, and written data that best describe the research phenomenon and allow for generalizations linked to the research case (Silverman, 2015). The core objective of using content analysis is to connect content with results in a way that identifies themes and enables interpretations that align with the obtained results. For these reasons, the researcher adopted the qualitative method to interpret large amounts of text concisely and systematically, effectively communicating the research findings and evidence (Bengtsson, 2016). This approach has been widely used in qualitative research and is credited with providing highly organized and concise summaries of key results (Saldana, 2016). As Creswell (2007) states, "The qualitative researcher uses complex reasoning that is multifaceted, iterative, and simultaneous." It is, however, noteworthy that this process is not value-free due to the interactive nature of data collection and interpretation. Parker (1994) emphasizes that acknowledging this subjectivity is crucial during the research process. Researchers should view interviews as social interactions while ensuring that their biases and prejudices do not influence data collection or interpretation (Creswell, 2007). Acknowledging this, the level of abstraction and conceptualization in interpretive case studies can range from suggesting relationships among variables to constructing a theory. Although the process may be subjective, scholars have argued that a critical awareness of these limitations can help mitigate potential gaps (Sharpe et al., 2009; Long et al., 2010).

The research followed a four-step process as guided by Carrington & Badger (2018). The first step involved familiarizing oneself with the data by transcribing the original text from the interviews. This ensured that the insights provided aligned with the research objectives and facilitated the appropriate categorization of the data collected. The second step involved assigning textual meaning to different aspects of the data. This was done to condense the information into a central, meaningful document that conveyed clear insights from the interviews. The third step was code formulation, where the researcher assigned codes and meanings to various data segments. This allowed for the identification and exploration of patterns and relationships within the data.

The assignment of codes involves using descriptive labels that accurately capture the different pockets of data that emerge from the qualitative process. This approach makes it easier to identify connections and meanings between variables, allowing for the reassignment or multiple assignments of codes in cases of data overlap. The fourth stage is the development of categories and themes. This involves assigning themes that address the key questions relating to the 4Ws: who, what, when, or where? Assigning these codes enables data differentiation and comparison, facilitating the appraisal of the codes so they can be grouped into different categories for comprehensive analysis. These four stages have been acknowledged in various studies, including those by Bollock (2018) and Hoibeck et al. (2018).

By adopting this method, the researcher maintained an open mind to identify, assign, and categorize meanings and codes to various aspects of the interview, effectively addressing the research questions. This approach facilitated the synthesis of findings, making them generalizable within the research design integrated into the research process. This aligns with the inductive research analysis discussed earlier in the chapter, enabling the researcher to condense extensive data to establish clear links with the research transparently. This method best captures the underlying insights from respondents, fitting them into the thematic variable attributions extrapolated (Liew et al., 2018).

5.10.1 Data Analysis Technique

For analysing the qualitative data, the researcher employed specific data analysis techniques. First, digital recordings from the interviews were transcribed. Each interview was transcribed independently, allowing for a thorough exploration of key themes that emerged from the data. To ensure the accuracy and validity of the transcriptions, they were sent back to the respondents for confirmation within two weeks of the interviews. This step ensured that the transcriptions accurately reflected the respondents' thoughts and feedback.

Considering that the interview data was interpretative, it was categorized into different conceptual groups to map the themes and ensure coherence with the central research objectives. These categories were then analysed using thematic analysis. This method involved identifying key themes or patterns from the interview data, which provided answers to the research questions. The thematic analysis allowed for the establishment of relationships between variables and determined the intersectionality between the data sets (Popay et al., 2006).

The strength of this approach lies in its ability to draw from both qualitative and quantitative sources, enabling a clear establishment of relationships between variables that address the overarching research questions embedded in the thesis (Bollock, 2018). One critique of the thematic approach is its inherent subjectivity bias, stemming from its interpretivist research philosophy, which inevitably frames preconceptions and assumptions (Silverman, 2010). However, the use of thematic analysis for qualitative analysis is widely acknowledged in the literature (Popay et al., 2006; Caswell, 2009). While subjectivity in its philosophical stance may affect its objective criteria due to human nature, recognizing this subjectivity and ensuring transparency in the triangulation process are ways to mitigate bias (Fleming & Noyes, 2021). Despite this, the thematic approach provides a valuable analytical framework that facilitates theory development and bridges gaps in the literature by allowing the aggregation of findings, identification of variations, and synthesis of results (Orben, 2016).

The data analysis for the qualitative interviews was based on an iterative process during data collection. This iterative process involved continuously adapting the key elements of the discussion emerging from the research to the overall research process. Insights gained from the pilot interviews were used to refine subsequent interview plans, ensuring the collection of critical data sets necessary for the research analysis (Moore et al., 2019). The initial interview pilot provided preliminary analysis and important feedback, revealing respondents' perspectives and various interpretations that emerged from transcribing the data into themes. The pilot was crucial in shaping the deployment of data, including the methods of dissemination to target respondents. Observations made by the researcher were meticulously recorded in a repository, with color-coding used to track emerging themes and how this data triangulated with the evidence. The researcher ensured that data transcription faithfully reflected the participants' words, maintaining the integrity of their feedback rather than introducing the researcher's bias. This approach also ensured that the main descriptive codes were accurately derived from the participants' expressions.

To ensure credible analysis based on the interview process, the research applied segmentation to the different themes identified (Gibbs, 2002). Segmentation involves applying preliminary codes to the data, touching on various themes and sub-themes emerging from the respondents' natural language (Cook, 2018). By segmenting the data, the main themes and sub-themes formed patterns of similarities that could be aggregated into a cohesive dataset. According to Bryman (2011), the main benefit of this process is the identification and formation of superordinate themes, providing a broader perspective on the patterns of responses and offering new insights into the research subject through the aggregated individual responses. Using codes was crucial in developing concepts around the interview responses. As Newman (2006) notes, this approach allowed for a comprehensive understanding of the research by interlocking individual insights into a conceptual framework that adds more meaning to the concrete data. Using codes, key themes were identified and consolidated, allowing for a deeper analysis and a clearer understanding of the relationships between emerging variables. This approach also facilitated the observation and merging of interrelated themes, enriching the analysis. Adopting codes enabled the filtration of data to eliminate partial and biased analysis, ensuring that only relevant information contributing to a coherent and comprehensive understanding of the research was included. This process enhanced the overall quality and reliability of the data aggregation.

5.11 Ethical Considerations

To obtain reliable and empirical data from experts in the UK construction industry ecosystem, the researcher needed to adhere to ethical standards. This involved seeking approval for the research instrument from the ethics committee of the University. Once approval was granted, the instrument was administered to respondents, meeting the minimum requirements outlined by ethical guidelines. Adhering to these guidelines, the researcher ensured that all participation was voluntary and based on informed consent. Additionally, responses obtained were kept confidential, respecting the privacy of the participants. To protect the data from theft and unauthorized access, the researcher implemented stringent measures for data protection and confidentiality. Anonymizing the participation further ensured that responses could not be traced back to individual participants. Furthermore, the researcher provided a preliminary page explaining the purpose of the research and assuring respondents that the data would be used solely for research purposes and not for commercial or any other unauthorized use.

5.12 Chapter summary

This chapter provides a detailed overview of the research methods employed to investigate the prospects and barriers to the adoption of robotics in the UK construction industry for the prevention of construction injuries. Recognizing the complexity of the research topic, a mixed-methods approach was adopted, integrating both quantitative and qualitative methodologies. This methodological choice was pivotal to ensure a comprehensive analysis that captures insights from both key research participants and existing literature on the subject. The rationale behind the selection of each research method was carefully deliberated, taking into account the nature of the research inquiry and the specific objectives of the study. By employing a mixed-methods approach, the research aimed to delve deeply into the multifaceted dimensions of robotic adoption within the construction industry, thereby enriching the analysis with diverse perspectives and empirical evidence. Moreover, this chapter elucidates the limitations inherent in each research element while providing a robust justification for their appropriateness in addressing the research objectives. By transparently delineating the strengths and weaknesses of the chosen methodologies, the research ensures the integrity and rigor of its investigative approach. This sets a solid foundation for conducting a comprehensive and nuanced examination of the issues surrounding robotic adoption in the UK construction sector.

The research philosophy underlying this study is positivism, chosen for its emphasis on objectivity and systematic, value-free analysis. This approach aligns with the core objective of the research, which seeks to derive conclusions that are generalizable and based on unbiased approximations of research truth. By adhering to positivist principles, the study aims to ensure the reliability and validity of its findings, facilitating broader applicability and relevance.

Furthermore, the research design is informed by these epistemological and ontological foundations, guided by the principles outlined in the research onion. This structured approach allows for the systematic collection and analysis of data, ensuring a rigorous and methodical investigation. By integrating both qualitative (interviews) and quantitative (survey) methods, the research enriches the depth and breadth of its inquiry, capturing diverse perspectives and insights from research participants. The utilization of interviews and surveys facilitates a dualistic perspective, enabling a comprehensive exploration of the research topic through firsthand accounts and experiences. This multifaceted approach enhances the richness of the research findings, providing a nuanced understanding of the complexities surrounding robotic adoption in the UK construction industry.

This approach was vital for the researcher to probe previously unaddressed gaps in the literature and gain insights into the slow adoption of robotic technologies and their efficacy in injury prevention within the UK construction sector. By obtaining perspectives directly from individuals involved in the industry, the research findings could closely align with the research inquiry and questions, ensuring relevance and applicability to real-world challenges faced by practitioners in the field.

CHAPTER SIX: Data Presentation and Analysis

6.0 Introduction

This section is primarily focused on presenting the data obtained from interviews conducted with key stakeholders in the UK construction sector for this thesis. As previously mentioned, ten individuals from various locations across the UK were approached to provide insights into critical questions surrounding the adoption of robotics in the UK construction industry and its role in preventing construction-related injuries. To maintain confidentiality, the information provided by these respondents has been anonymized and labelled 1-10 to represent their respective contributions. The interview data collection process involved assigning codes to the responses. Subsequently, these codes were categorized into themes, shaping the content of this section based on the key insights provided by the respondents.

6.1 Emerging Themes from the Interview

The interview data revealed five key themes: the utility of robotic technology in preventing construction injuries, barriers to its adoption in the UK construction landscape, pathways for integrating emerging and existing robotic technology, mechanisms for supporting robotic adoption, and the intersection of safety and technology. The majority of respondents affirmed the utility of robotics in the construction industry and its potential benefits, especially in reducing construction-related injuries. Respondents expressed optimism about the potential for innovations to reshape the relationship between safety and technology, highlighting safety and technology as prominent themes in the findings. The data suggests that robotic technology offers significant benefits for construction, a sentiment supported by existing literature. However, respondents acknowledged that the successful adoption of robotics depends on factors such as scalability, functionality, cost, and alignment with safety protocols. Despite these considerations, there is considerable potential for the construction industry to leverage robotics to enhance safety.

The majority of respondents acknowledged the broader utility of emerging technologies beyond robotics in the construction industry. This encompassed the incorporation of sensor technology, IoT, and big data, which can enhance not only safety but also operational efficiency. They highlighted the potential for construction workers to leverage these technologies and collaborate with robotics to advance their integration on construction sites. For example, one respondent emphasized that increased awareness and utilization of robotics could mitigate hazards linked to work-related overexertion, overuse, and musculoskeletal disorders. However, a notable concern that surfaced was the perception that these technologies are viewed as a one-size-fits-all solution for preventing all construction-related injuries. This concern is particularly relevant given the evolving nature of robotics and its components, such as metal parts, which may introduce new risks without proper training. Despite this concern, many interviewees expressed optimism about the increasing role of robotics in enhancing safety on construction sites. However, they also emphasized that the extent of this adoption would depend on the evolving landscape of technological development and investment practices in the UK.

The second emerging theme delved into the myriad barriers hindering the adoption and implementation of robotics within the construction industry and across major sites. These barriers encompassed technical challenges, primarily centered around the skill requirements necessary for effectively utilizing the technology and ensuring its seamless integration. Additionally, respondents highlighted difficulties associated with the proper handling of these technologies, underscoring the need for comprehensive training. Furthermore, concerns regarding the perception of robotics were raised, including apprehensions about the potential for these technologies to undergo a cycle of rapid advancement followed by decline in their utility—a phenomenon commonly observed in the technology sector. This perception aligns with the principles of the technology acceptance model, which emphasize users' perceptions and the perceived ease of use of a technology as pivotal factors influencing its adoption and utilization.

Respondents also highlighted the concern regarding the upfront cost of adopting robotic technology. They pointed out that the initial investment required for these technologies is perceived as a significant barrier to their widespread adoption in the UK. According to their perspective, this upfront cost poses challenges in conducting cost-benefit analyses and raises questions about the return-on-investment for construction stakeholders before making a final decision on implementing robotic technology in construction sites.

They emphasized that market demand, client perceptions, and the financial implications of robotization for building costs and site design are all key factors influencing the feasibility of adopting robotic technology for construction projects. In their view, evaluating the cost-benefit ratio of adopting robotic technology involves carefully considering the financial gains versus the costs of implementation and assessing the availability of technical expertise required to operate the robotics. The findings from this theme revealed the inherent challenge of identifying the most suitable technology for adoption in the construction industry, considering the specific conditions of construction sites. Respondents expressed concerns about construction stakeholders' hesitation to embrace technology due to uncertainty regarding profitability and the high investment costs associated with adoption. However, opinions among respondents varied regarding the use of monitoring technology to enhance safety on construction sites, with some expressing apprehension about surveillance and privacy implications.

The theme of integration delves into the pathways for incorporating emerging and existing robotic technology into the construction industry. This is crucial given the necessity of collaboration between robotic adoption and human workforces. Respondents emphasized the importance of this integration in determining the feasibility of these technologies and their ability to effectively prevent injuries in construction settings. Interviews highlighted the need to involve technology companies in long-term strategies for developing, testing, and implementing technology within the construction industry. Additionally, respondents stressed the importance of integrating robotics while considering the various stakeholders involved, ensuring that the potential benefits and capabilities of these technologies are effectively communicated throughout the sector. This is particularly important given the diverse range of construction stakeholders responsible for ensuring safety within the UK construction sector.

Respondents highlighted the significant cost implications associated with integrating robots into existing systems and technologies, which is crucial for determining their compatibility and interaction with humans. This cost factor is closely linked to the challenges of ensuring that robots can effectively integrate and interact with other technologies, such as drones, sensors, and cameras, at a system level. Compatibility issues, including communication protocols, further complicate integration efforts. Additionally, respondents emphasized the substantial amount of data generated by robots and the accompanying privacy and data sensitivity concerns. These concerns extend beyond the use of robots themselves and require careful consideration in integration planning. An essential element raised by respondents was the importance of the seamless integration of robots into workflows. Without achieving compatibility, integrating robots with human activities becomes challenging and may diminish their effectiveness in preventing construction injuries.

Some experts emphasized that the inevitable adoption of robotics in construction hinges on the extent to which construction workers familiarize themselves with the intricacies of robotic systems and associated technology. This aligns with the concept of creating space for innovation as a developmental necessity, rather than humans ceding ground to technology. For instance, R1 highlighted the need for a transitional phase, explaining the process required for the construction industry to fully embrace robotics at a higher level. This transition would entail extensive retraining of the existing workforce. Given the challenges posed by an aging workforce in the UK, this training may necessitate a comprehensive understanding of mastering robotics and automation while also recognizing the complementary role of human strength, such as with exoskeletons and robotic arms.

Against the backdrop of the five themes gleaned from interviews with key informants, this section delves into their analysis concerning the nexus between the adoption of robotics and the prevention of construction injuries in the UK. The insights presented here are rooted in this exploration and are specific to the UK context. The analysis stems from both qualitative and quantitative research, including interviews with key informants in the construction industry in the UK and literature review data. Notably, key informants encompassed experts from various sectors within the UK construction industry, ranging from small to large construction companies.

Table 6: Thematic Summary of Interview Data

Theme	Description	Why It Was Selected	Significance to Study
1. Utility of Robotic Technology in Preventing Injuries	Focused on the benefits of robotics in minimizing construction-related injuries and improving safety outcomes.	Repeated affirmations by interviewees regarding safety improvements and value-added outcomes of robotics.	Highlights the core aim of the study—assessing whether robotics can improve occupational safety in construction.
2. Barriers to Robotic Adoption	Encompasses technical, financial, and perceptual obstacles such as high costs, skills gap, and stakeholder hesitancy.	Emerged frequently across interviews as a reason why robotics hasn’t been widely implemented in UK construction.	Identifies key constraints limiting robotic adoption, essential for shaping policy and industry strategies.
3. Pathways for Integration	Describes how robotics and related technologies (e.g., IoT, sensors) could be meaningfully embedded into workflows.	Participants repeatedly mentioned integration as a condition for robotics to be effective and sustainable.	Offers insight into necessary infrastructure and stakeholder alignment to scale robotics in construction.
4. Mechanisms Supporting Adoption	Highlights institutional, market, and workforce-related factors such	Interviewees stressed external enablers like client demand and	Informs how government and industry bodies can support adoption

	as investment, training, and market readiness.	training as catalysts for adoption.	through investment and policy tools.
5. Intersection of Safety and Technology	Focuses on how technology (beyond robotics) intersects with safety, including risks like surveillance or privacy.	Emerged from nuanced responses that acknowledged both pros (data-driven safety) and cons (privacy concerns).	Encourages a holistic view of technology's dual role in enhancing safety while potentially introducing new risks.

6.1.1 Construction Industry and Robotics in the UK

Insights from respondents on the state of robotic technology in the UK revealed several key points. Robotics is recognized as a crucial technology that is already shaping the innovation ecosystem, particularly in automation and digital transformation. They are seen as important advancements poised to revolutionize the construction industry in the UK. Despite the construction industry experiencing significant transformation and embracing advanced innovative technology as part of the Industry 4.0 shift, the adoption of these technologies is perceived to be slow compared to other regions in Asia and Europe. Although there have been significant efforts to accelerate these technologies and challenge the status quo of traditional construction, much remains to be done to fully integrate robotics into the sector.

This perspective is based on two key aspects of the UK construction industry that significantly influence the adoption of robotics. The first aspect is the perception of robotics within the UK. While recognized as important, robotics is not as highly regarded or widely adopted as it is in other regions. The second aspect is the policy climate regarding robotics. Despite significant momentum for robotics in other areas of the UK economy, the construction industry has not seen a similar level of uptake. Respondents indicated that economic concerns are a major barrier. The cost of acquiring and implementing new technologies is high, and there is uncertainty about the return on investment, especially when robotics is seen as a replacement for existing jobs rather than a tool for preventing injuries. Additionally, there is apathy toward the slow shift to robotics in the UK construction sector. One major issue is the cost and scalability of these technologies, which can be prohibitive for meeting specific project needs. Another concern is the suitability of robotics for different types of construction projects. Many robots are not versatile enough to be used in both infrastructural and civil projects due to the varying nature of construction sites.

However, there was a strong consensus on the necessity for the UK to develop and enhance indigenous technologies for robotics. As Respondent 1 noted, "*The importance of developing indigenous capacity for advanced robotics transcends the present and extends into the future, reshaping how tasks are performed and enhancing the quality of outcomes."* This insight underscores the need to view robotics not merely as an adjunct to construction but as a critical component of the inevitable technological advancement that the UK must embrace. Furthermore, the impact of robotics on employment was a significant concern. One respondent highlighted that.

> *While the introduction of robotics into conventional construction may have inevitable consequences, these changes are primarily long-term and ultimately lead to improved construction quality and efficiency. '* [R1]

Embracing robotics is seen as essential for keeping pace with technological progress and ensuring that the UK remains competitive in the global market.

The respondents emphasized that technological innovation has long been a dominant force driving progress, and the shift to robotics must be embraced similarly. They noted,

> "*For many years, technological innovation has been a dominant feature of current advancements. The shift to robotics needs to be embraced likewise; the UK needs to swim or sink, adapt or stay stagnant. Robotics and automation technologies are bound to become more prominent in the coming years, and it does greater industrial good if they are acquired, deployed, and used in various capacities to achieve different purposes in the construction industry."* [R1]

However, there was a caveat regarding the scale and pace of this transition. The respondents stressed the importance of ensuring a just transition to automation technologies without causing significant disruptions to construction work. They highlighted that many of these technologies require time and skill to learn, understand, and operate, with additional software capabilities needed to meet specific needs. The gradual introduction of these technologies is crucial, especially if the goal is to prevent construction injuries or improve health and safety outcomes. Ensuring that construction workers can effectively collaborate with these technologies will be key to their successful integration.

One respondent emphasized that the integration of robotics into the construction industry requires a robust learning pathway. Experts highlighted the importance of creating a strong educational framework that aligns with existing construction practices to ensure seamless integration. This integration is necessary because the technical complexity of robotics can obscure its functionality. Developing the skills needed to effectively use robotics is crucial for successful human-technology collaboration. Furthermore, this approach will facilitate machine learning and help workers adapt, enabling them to view robotics as an integral part of their work rather than an impediment.

Changing perceptions and building human-machine collaboration are crucial for fostering trust in the effectiveness of robots in construction. Respondents emphasized that one of the inherent challenges lies in the cost implications of acquiring and scaling these technologies for widespread use across the industry. Another significant challenge is the learning curve associated with these technologies. Thus, it is not just about acquiring robotics but also about integrating it into daily operations and normalizing its use within the construction workspace. This process is essential for ensuring that robotics becomes a seamless part of the construction experience, enhancing productivity and safety.

Experts emphasized that advancing towards integrated robotics in construction must prioritize research and development to keep pace with the industry's growing needs. This ensures that emerging technologies are applicable and effective in enhancing efficiency, productivity, and innovation. The UK already possesses a robust repository of knowledge and skills essential for catalysing robotic innovation in construction. As one respondent noted,

> "*Much of the system knowledge, infrastructure, and control mechanisms needed for the implementation of robotics in the UK construction sector are already in place. However, the industry still needs to address how it can adapt existing technologies and integrate them with emerging ones to meet its evolving needs."* [R4]

This adaptation and integration are crucial for leveraging the full potential of robotics in construction.

One respondent highlighted the increasing significance of miniaturization in robotics, emphasizing its versatility, compactness, and agility in performing various tasks with precision and efficacy. They suggested that the construction industry should leverage these advanced technologies to address evolving needs, moving away from conventional methods. Another respondent echoed this sentiment, pointing out the current lack of connectivity on construction sites, which leads to fragmented work and hampers real-time data collection, thereby increasing the risk of accidents and fatalities. This aligns with recent findings indicating that many construction sites in the UK still rely on paper plans rather than digital tools for project management, particularly in smaller companies. While larger firms may utilize digital tools, their widespread adoption remains limited. Consequently, the absence of real-time data tracking, including the integration of robotics for various activities, represents a significant gap in the UK construction industry's current operations.

Respondents emphasized the potential of robotics to enhance construction safety by increasing productivity and reducing exposure to hazardous risks. They viewed robotics as a solution to address the impending workforce challenges resulting from retirements in the UK construction industry. One respondent highlighted the need for the industry to embrace digitalization and connectivity to prioritize safety effectively. Furthermore, respondents shared examples of current robotic applications beyond injury reduction, such as inventory management, site patrolling using robotic dogs, and inspection of sites suspected of leaking. Additionally, drones were mentioned as tools for collecting and analysing aerial data, providing valuable insights for construction activities.

6.1.2 Prospects for Robots in the UK Construction Industry

Insights from experts underscore the rising prominence of robotics within the UK construction industry, signaling varied, multidimensional, and inevitable prospects for its adoption. Respondents highlighted how technology is reshaping the construction landscape and broader innovation ecosystem, with the primary aim of enhancing efficiency, productivity, and mitigating construction-related injuries. Despite previous perceptions of the UK construction industry as low-tech, recent years have witnessed a significant shift towards technological integration, driven by the development of more complex building designs requiring innovative solutions. The prospects for robotics adoption were viewed as closely linked to the industry's demand for technological advancements. Respondents emphasized that the construction sector continually seeks innovative solutions to address longstanding challenges, with robotics emerging as a promising avenue for tackling these issues. As one respondent articulated,

> "*The UK construction industry is constantly in search of innovative solutions to solve longstanding issues and challenges, and robotics seems to be one of the many solutions poised to address some of these challenges*." [R3]

Respondents highlighted one of the primary prospects of robotics as catalyzing the drive to drive productivity, efficiency, and quality in construction projects. Given the inherent complexity and strict timelines of construction efforts, the use of robots to streamline and accelerate project delivery serves as a significant motivator for companies to explore their acquisition and adaptation. Robots offer the capability to operate autonomously or semi-autonomously, programmed to undertake repetitive tasks and enhance construction processes. Additionally, their utility lies in their ability to perform tasks prone to injury exposure and project delays, thereby reducing labour costs and minimizing wastage. Moreover, many robots operate on programmable algorithms, enabling them to execute tasks with precision, speed, and consistent quality. Leveraging advanced digital platforms, including artificial intelligence, these robots ensure efficient project delivery through data analytics, smart computing, and rapid analysis, surpassing human capabilities in speed and accuracy.

Another significant aspect highlighted by respondents pertains to the utilization of robotics as an indication of the construction industry's transition towards digital technology and automation. Present sentiments within the industry underscore these advancements as primary indicators of its level of sophistication. Modern construction methods not only embrace innovative building techniques but also reimagine how technology influences building planning, control, and project outcome measurement. They facilitate and optimize project planning, enhance design functionality in 3D, and enable data-driven execution. These prospects are already evident, with many construction companies in the UK increasingly relying on digital technologies to transform their construction work. This transformation offers added advantages such as enhancing accuracy in project delivery, ensuring consistency in work quality, providing precision in robotic operations, and instilling greater confidence in quality assurance through improved delivery interfaces.

Many respondents highlighted that specialized robotic technologies tailored to meet identified needs in the construction industry hold significant potential for enhancing safety measures across construction sites. Respondent 1 emphasized that.

> "*...implementing robotic systems as solutions is aimed at ensuring that the functionality design of robots enhances construction safety outcomes. For instance, the use of exoskeletons mitigates the risk of common overexertion injuries, including assisting in lifting and moving around the construction site.*" [R4]

Utilizing robots for specific functionalities was also seen as an advantage for improving specialization and the potential for future iterations of robots to further enhance solution designs. Respondent 5 highlighted another promising prospect: the collaborative use of robots with humans in the construction industry. They remarked,

> "*The concept of humans and machines collaborating has transitioned from science fiction to practical reality. Today, robots and humans working together are reshaping the future of construction, where efficiency and productivity gains are inevitable benefits*." [R5]

With advancements in AI, sensor technologies, and IoT, these robots enhance situational awareness in construction environments, thereby improving safety and averting potential hazards and deviations that could compromise project integrity. For example, modern robots have the capability to monitor air quality, vibrations, sound, and temperature, crucial indicators for enhancing safety protocols and environmental conditions on construction sites.

Respondent 4 highlighted another promising aspect: the integration of robots with sensor technology for site alert, managing confined spaces, vehicular mobility within the construction site, and enhancing resilience in construction. This sentiment was echoed by Respondent 3, who emphasized the utilization of autonomous robots for monitoring gas leaks, elevated carbon dioxide levels, and other potential hazards like water leaks and increased ambient temperatures. These robots serve multifaceted purposes beyond physical safety, akin to wearable technologies. Additionally, another respondent identified computer vision integrated with robotics as a game-changer. This technology harnesses visual imagery to gather data about construction sites, which can be analysed to improve safety measures, prevent hazards, and address deviations. Moreover, these insights are seamlessly integrated with BIM, enabling data visualization crucial for monitoring and analysing construction projects.

The collaborative integration of robotics was deemed crucial, as it enables construction workers to better understand and interact with the technology, fostering trust and knowledge about its application. This collaborative approach showcases the potential future of construction projects, leveraging the combined capabilities of both robots and humans. Respondent 5 emphasized that as this collaboration between humans and machines advances, it is expected to significantly enhance the quality and efficiency of construction output. Moreover, it paves the way for advanced integration of robots and humans to tackle complex tasks. This approach embodies the concept of smart construction, which not only leverages human abilities but also integrates machine intelligence for construction analysis and execution.

An important aspect raised regarding the integration of robotics is its potential to address skilled shortages in the UK construction industry and labor force needs, particularly in light of the aging workforce and diminishing pool of skilled talent. Respondent 6 highlighted that while this concept is still evolving, widespread adoption of robotics holds immense potential to mitigate the skill and labour shortages expected to impact the UK construction industry. This shortage has been exacerbated post-Brexit, leading to the departure of skilled individuals back to Europe. Moreover, robots can perform complex tasks autonomously, thus enhancing opportunities to improve productivity, efficiency, and construction timelines, irrespective of human intervention.

However, respondents emphasize that the feasibility of this scenario hinges on several factors, including the economic implications for unemployment, the procurement costs of these robots, and the extent to which the industry intends to adopt them according to UK construction standards. This consideration is set against the backdrop of existing regulatory frameworks in the UK, which mandate that robotics and innovations meet industry standards, regulatory benchmarks, and sustainability criteria. These criteria prioritize environmental concerns such as reducing carbon footprint, emissions, resource efficiency, minimizing waste, and promoting energy efficiency and conservation, thus encouraging the adoption of cleaner and greener alternatives.

The potential of utilizing robotics to achieve these objectives has been underscored by numerous experts interviewed. They recognize that modern iterations of robotic technologies are strongly aligned with clean energy and environmental considerations, particularly optimized for material handling. However, many of these robots are not domestically produced in the UK; they are often imported, necessitating rigorous checks to ensure compliance with various environmental laws before implementation. This links the prospects of robotics to a complex dilemma. Firstly, robotic adoption must align with its intended purpose, tailored to meet the specific needs of the construction industry in the UK. Additionally, the substantial upfront costs of acquiring, implementing, and deploying robots serve as a significant determinant of their adoption. While robotic infrastructure exists in the UK, it comes at a considerable expense. Moreover, there's the hurdle associated with weighing the long-term benefits against the initial investment required to set up robots.

Another respondent highlighted the utility of robotics in advancing sustainability discourse within the construction sector in the UK. Sustainability has emerged as a pivotal element in the UK's trajectory towards achieving net-zero emissions by 2050, with clean technologies being deemed crucial in this endeavour. According to respondent 7,

> "*The drive towards sustainable and clean technology use in the UK cannot be achieved without energy-efficient and zero-carbon emissions technologies such as robotics, which operate electrically or with battery power. These robots produce no carbon footprint and utilize alternative energy sources that are clean and green*." [R7]

For instance, exoskeletons can be employed for operating and lifting in construction work, primarily relying on batteries rather than fossil fuels for power.

The respondents underscored a confluence of factors driving the prospects of robotic technology. These include labour optimization, enhancing sustainability discourse, regulatory compliance, and improving workflows and processes. They emphasized that the rapid adoption of robotics hinges on robust training and supportive mechanisms, which largely depend on stakeholders who are the gatekeepers of technology adoption within their organizations. While there is a high appetite for robotics in construction, adoption remains sluggish. However, leveraging these technologies can expedite the trajectory of robotics in UK construction, aiding the sector in overcoming its current challenges.

6.1.3 Robotic Technology and Construction Injuries

Respondents emphasized a strong inclination towards utilizing robotic technology to address various construction-related injuries. According to Respondent 1,

> *Robotics offers a solution to numerous injury challenges in the UK. They can provide support, protection, manoeuvrability, and adaptability in diverse situations, enhancing their utility and relevance in construction work." The significance of robotics was underscored not only in mitigating construction workers' susceptibility to injuries, including the risk of fatalities, but also in performing essential functions crucial for enhancing safety at construction sites.* [R1]

This is particularly crucial given the inherent dangers and hazards associated with construction activities, such as falls from heights, overexertion, strains, sprains, overextension, vehicular accidents, and the risk of deviations and other unforeseen incidents, all of which expose construction workers to various dangers.

As noted by respondents, the utilization of robotics holds the potential to prevent numerous injuries, thus mitigating the risk of severe bodily harm. Robotic innovations, such as full-body robotic support suits, offer comprehensive protection for the entire body, aiding in movements and tasks that impose significant strain on muscles, ligaments, and bones.

Respondent 5 emphasized the critical role of robots in repetitive tasks on modern construction sites, stating that "any well-meaning organization should strive to acquire robots that help prevent injuries proactively, rather than waiting for accidents to occur." Robots function as both preventive measures and supportive adjuncts for workers, akin to personal protective equipment, as highlighted by Respondent 4. In a preventive capacity, robots equipped with sensors and Internet of Things technology detect hazards and serve as early warning systems for construction workers, thereby averting dangers such as fires, gas leaks, temperature fluctuations, and other hazards prevalent in construction environments. Additionally, respondents emphasized that robots are not autonomous entities but rather exist to support construction workers, enhancing the overall safety and longevity of the construction site. As Respondent 4 articulated,

> "*Robots function to make the construction site better, safer, and ensure the well-being of construction workers*." [R4]

Given the prevalence of injuries within the construction industry, respondents highlighted numerous benefits of employing robotics to address this issue. These benefits encompass enhanced productivity, reduced physical strain, minimized instances of illness, fewer sick hours, and overall improvement in the quality of construction work and worker experience. Moreover, advancements in research and the design of new robotic technologies indicate a significant focus on incorporating cutting-edge detectors to identify potential risks of injury exposure and promptly alert construction workers. As noted by Respondent 3,

> "*Innovations in robotic design prioritize user-centered principles to ensure intuitive, user-friendly interfaces that seamlessly integrate with existing workflows*." [R3]

This approach ensures that robots are efficiently utilized, prioritizing ergonomic working conditions and enhancing usability, resulting in higher user satisfaction scores. Such design considerations make robots adaptable to workers and improve interaction between robots and their applications, including how intuitive software interfaces can accelerate the understanding of human physiology and provide alerts regarding imminent threats to worker safety.

However, respondents noted that the integration of this technology is not without potential drawbacks, particularly concerning privacy, data security, and confidentiality risks. As robotics becomes more capable of not only sensing, supporting, and directing but also collecting real-time data and computing analytics, concerns about the misuse or exposure of sensitive information loom larger. Respondent 2 aptly points out,

> "*This is a case of innovation with consequences, and while these cannot be eliminated from the equation when adopting robotics, the transition must be accompanied by enhanced protection against the issues associated with these technologies*." [R2]

Another significant issue raised is the level of skill and training required for the seamless integration of these technologies into the construction industry. Without adequate training, there is a risk of increased hazards, including potential damage to the robotics, which could adversely impact the balance sheet of construction companies. Additionally, the recurring factor of cost was mentioned as another obstacle against the widespread adoption of robotics.

6.1.4 Barriers and Challenges to Robotic Adoption in the UK Construction Industry

The barriers and challenges impacting robotic adoption in the UK revealed several insights from experts. Respondents affirmed that, considering the balance of utility and relevance, the benefits of using robotics are a welcome development for the industry, particularly in preventing construction injuries and hazards. For instance, drones significantly reduce or even eliminate the risk of falls from heights during inspections. Similarly, bricklaying machines can perform the work of multiple bricklayers in a fraction of the time, enhancing efficiency and productivity. However, the challenges to adopting robotics primarily stem from technical considerations. Finding technology that meets the requirements of construction sites is not a straightforward task.

Because real-time technologies like automated robotics may not seamlessly integrate or withstand the rigors of construction sites, adapting them for such environments poses challenges. As noted by respondent 4,

> "*The applicability of technology from other sectors often doesn't directly translate to the construction environment, given the unique conditions such as varying weather conditions and force majeure incidents like snow, rain, sunshine, and storms*." [R4]

Respondent 2 echoed this sentiment, highlighting resilience as a major concern in implementing construction robotics, as failure to withstand harsh construction environments limits their sustained use. Moreover, certain tasks within the construction domain may not be conducive to robotic deployment. For instance, performing concrete work in marshy or waterlogged sites can impede the mobility of machines.

Resilience encompasses functionality, durability, usability, and the ability to withstand the hazards inherent to construction sites. However, certain heavy-duty robots, designed to be stationary, may face limitations in mobility, restricting their utility across various functions. Additionally, robots programmed with real-time data capabilities may encounter connectivity issues prevalent at most construction sites, where signal interference can disrupt data transmission. Moreover, if a machine's primary role on the construction site relies solely on obtaining real-time data, dependence on this function may risk data loss in the event of connectivity issues.

Another challenge identified by respondents that currently hinders the adoption of robotics revolves around the perception of robotics among key construction stakeholders. As noted by respondent 3,

> "*What is observable across the sector is that larger companies have a bigger appetite to adopt robotic technologies, including investing in numerous ongoing research innovations across different laboratories in the UK. However, the investment appetite is not the same with smaller companies due to resource constraints*." [R3]

This disparity in advantage, as agreed upon by respondent 6, is cyclic and characteristic of the underlying competition in the construction industry. This discrepancy highlights the diverse perspectives on how these robots can be adopted to address the ongoing needs of the construction industry, especially considering the benefits they offer in improving efficiencies.

Smaller companies, as noted by respondents, typically perceive robotics as cost-prohibitive and overly complex for implementation and maintenance. Procuring this technology entails not only a one-time purchase but also requires skill, training, and maintenance to ensure optimal performance. Furthermore, respondents highlight that, relative to its cost, smaller companies are mostly deterred by the long-term investment required for safety and efficiency improvement compared to retraining staff for more efficient methods. While the perception of robotics remains split among stakeholders, the key concerns regarding the speed of adoption will depend on how these perceptions are addressed and how opportunities to procure these technologies are equalized to increase access and availability, as noted by respondent 4.

Another challenge highlighted in the interview insights is the skepticism surrounding robotic adoption within construction circles. Concerns include the perceived risk of construction workers losing their autonomy, dependence on machines, unfamiliarity with new technology, resistance to change, and apprehension regarding job loss. Professionals in construction and safety, as noted by respondent 1, emphasize the need for proper health and safety standards to be developed to ensure that the integration of robotics into the construction site does not increase the risk of hazards and injuries, but rather enhances efficiency and productivity. This entails establishing manuals for operation, conducting training and reskilling exercises for staff, implementing guidelines for regular maintenance, standard operating procedures, and safety protocols for the use of technology in the worksite.

Additionally, as respondent 2 highlights, industry associations and trade unions advocating for construction workers can play a pivotal role in influencing the pace and extent of robotic adoption. They would aim to ensure that while robotics promises improvements in safety, efficiency, and productivity, they are introduced with due consideration for existing workers, avoiding exploitation, wage cuts, ethical concerns, or job displacement. Moreover, as noted by respondent 3, lobbying groups within the construction industry are likely to influence government policy decisions and agreements. They may seek to slow down the adoption of robotic technology or secure additional funding, ensuring that, beyond economic considerations, governments and construction stakeholders carefully consider data risks, privacy concerns, liabilities, and existing regulatory frameworks governing the use of such technologies.

According to respondents, the perception of construction robotics may transform in the coming years as the technology becomes more prevalent and the UK intensifies its efforts towards advancing robotics. However, industry experts emphasize that the extent of this transformation hinges on factors such as the cost, complexity, and alignment with key issues related to technology adoption. These include building trust and transparency, opportunities for learning, and understanding how robot-human interaction can function and coexist in the industry effectively. The goal is to unlock the full potential of the technology while addressing the legitimate concerns that construction stakeholders have regarding its integration into the industry.

Another challenge identified in the interviews is the economic barrier associated with adopting robotics in construction. Apart from the significant initial investment required, uncertainties regarding the cost turnaround of the technology, profitability, financing, and implementation raised critical concerns among respondents. Respondent 9 highlighted that while technology undoubtedly has a place in the construction industry, the extent of its adoption depends on its pricing and its ability to function optimally. Additionally, there is concern that many of these technologies are novel and imported from overseas, making it challenging to assess their suitability for investment and whether there is sufficient competence to handle their repairs, upgrades, and maintenance when needed. Thus, economic and financial considerations are paramount in determining the feasibility of adopting these technologies.

Respondent 10 concurred with this sentiment, stating that

> "*The industry stands to benefit greatly from technology, and while we can make a case to higher-ups, it's not always guaranteed that these requests will be approved within project budgets."* [R10]

This reluctance is rooted in the understanding that there are limited resources available to justify the use of robotics for construction safety, particularly if it risks exceeding the budget without immediate tangible benefits to justify to clients or top management, especially in the short term. Additionally, respondents acknowledged that while the usefulness of deploying these technologies has been recognized by various stakeholders in the construction industry, the idea of fully digitalizing the construction industry in the UK is still in its early stages of development.

Respondent 8 emphasized,

> "*We have seen efforts towards ensuring that the construction industry in the UK catches up with its counterparts overseas, with government announcements of proposed investments in the sector. However, companies bear the initial costs, and for smaller firms with limited financial backing, these upfront expenses may not be justifiable when considering the broader potential of enhancing safety, which has not yet been fully realized by the construction industry at large*." [R8]

Similarly, respondent 10 highlighted, "*The idea of using technology for safety improvement has been a recurring agenda item, as many aim to reduce accidents and fatalities. While the technology is available in the market, the main barrier to its widespread implementation is the cost involved."*

Respondent 1 echoed this sentiment, noting,

> "*In most cases, due to the competitive nature of the construction sector for procurement contracts, projects are awarded mostly to the highest bidder, who*

> *typically are larger companies with deeper pockets. While smaller companies may occasionally secure project contracts, investing in new technology that may not yield immediate profits or long-term benefits often ranks lower on their list of priorities*." [R1]

Furthermore, insights from the respondents highlighted the challenges of implementing real-time monitoring systems and their use on construction sites. They expressed skepticism about this technology, citing concerns that it might be perceived as intrusive and controlling, potentially impacting worker behaviour.

Respondent 1 affirmed,

> "*Computer vision in robotics and drones represents significant innovations, but there's concern that some may perceive them as tools for spying on workers and exerting management control on-site*. [R1]

Moreover, there are legal and ethical implications to consider. Ethically, questions arise regarding the extent to which intrusive or monitoring technologies should be allowed in the construction space. Legally, issues of privacy, data sharing, and the nuances of surveillance come into play. Additionally, the use of such technologies is governed by laws that extend beyond the scope of work, providing construction workers with grounds to withdraw consent if they feel these technologies are being used for purposes other than intended."

"This illustrates the intricate web of technology, where each layer of innovation carries inherent implications if other considerations are not integrated. Both Respondents 4 and 8 concur that these technologies, particularly robotics, could hinder the level of trust construction workers have in collaborating with them in the work environment. While these technologies are designed to enhance safety, the potential distrust they may evoke could create discord, thereby exacerbating safety concerns. As Respondent 4 emphasizes,

> *'Safety is most effective in an environment of mutual trust between workers or between humans and robots*.'" [R4]

The resistance to change associated with innovations, as highlighted above, is a common phenomenon often accompanied by a change management cycle. Despite the purported utility or benefits of new technologies, resistance is often inevitable. As Respondent 5 emphasizes, the willingness to adopt or embrace a new technology should stem from an understanding of its intended purposes as a solution or its broader potential benefits and capabilities that align with existing systems. However, distrust of robotics is not uncommon, as innovations often render previous ones obsolete. Respondent 1 observes that.

> '*Just like the advent of mobile phones phased out paid phones, new technologies typically herald change, which, whether good or bad, often evokes mixed feelings among those affected'*. [R1]

Furthermore, the impetus for change often originates from higher levels of management rather than from construction workers themselves. As Respondent 6 points out, '*management is the primary driver of decisions regarding the adoption of new technology*.' Insights reveal that the perception of leadership or management significantly influences whether the technology will be adopted and the change management processes required to transition from conventional methods to modern approaches facilitated by new technological innovations. While this may sometimes result from a lack of understanding of the benefits that robotics offers compared to traditional methods, it often boils down to whether management gives a definitive yes or no before proceeding to the next phase of employee consultation. In certain cases, as noted by Respondent 3,

> '*Employees may initiate the process, but ultimately, it is management's decision whether they have the risk appetite to transition from conventional to modern approaches for achieving safety and productivity*." [R3]

One key aspect highlighted in the interview was the relationship between robotics and the environment, particularly concerning safety. Compliance with safety measures isn't universally embraced across the construction industry. While some stakeholders prioritize safety as a fundamental aspect of their work, this isn't always the case for every company, as levels of safety compliance vary. As noted by Respondent 2, this discrepancy is particularly apparent.

> '*When one considers that robotics aims to reduce hazardous exposure, but they can only function effectively if there are existing safety guidelines in place for them to build upon*.' [R2]

This underscores the interconnected nature of safety and technology. Utilizing robots effectively necessitates careful consideration of the intended outcomes and the provision of an enabling environment by organizations to ensure both the success of robotics and the achievement of safety goals.

As noted by Respondent 7, collaboration serves as a two-way street, linking a company's long-term vision for technology integration with the need to ensure short-term functionality and profitability. Respondent 5 further emphasizes that collaboration reflects companies' intentions to test, lead, and develop technology, while also promoting safety through the normalization of collaborative efforts facilitated by robotics. This fosters a more viable ecosystem where both robots and humans thrive, with technology implementation tailored to their competencies and functions, prioritizing solutions and support for workers over concerns about dependency or streamlining. Respondent 4 underscores the importance of collaboration for achieving safety goals, stating that cooperation between humans and robots is essential. However, Respondent 5 highlights that the extent to which this collaboration is facilitated largely depends on management's ability to develop the necessary skills and competencies to enable a smooth transition without the complexities of acquiring entirely new technical training.

6.1.5 Industry Readiness and Emerging Technologies in the UK Construction Industry

Respondents noted a growing need for robotization over the years, as more sectors gravitate towards automation or embrace it. The proliferation of artificial and emerging digital technologies has spurred the fusion, integration, diffusion, multimodality, and linkage of various innovations in advanced scientific fields. Insights emphasized how emerging technologies enhance the dynamics and capabilities of robotic systems, shaping the future design of robotics. This perspective stems from the understanding that innovation is continuously evolving, mirroring the evolving needs of the construction industry. Thus, there's a pressing demand for AI and its associated technologies to establish a foothold in the digital landscape, particularly in robotics and automation.

When asked about their readiness and anticipation for emerging technologies beyond robotics that are expected to shape the industry in the coming years, respondents acknowledged the UK's robust infrastructure and strong research and development background. However, Respondent 1 highlighted the importance of ensuring that curriculum development aligns with industry needs, especially as technologies continue to advance, pushing the boundaries of what is achievable. This includes preparing for the future of computation, algorithms, software utilization, big data analytics, and identifying cutting-edge solutions to address emerging challenges. Staying ahead of the curve, anticipating market demands, and leveraging technologies to expedite construction processes were also emphasized as crucial considerations for the industry's trajectory.

Respondent 8 highlighted that while research and development are currently driving the pace and forecasting the future of robotics, they do not predict how humans will adapt to and utilize these technologies to their fullest potential. Moreover, respondents emphasized that the advanced use of robotics on construction sites will necessitate a broader range of engineering expertise, including software development. This ensures that teams can optimize the capabilities of robots, enabling engineering teams to tackle complex challenges and enhance performance, reliability, and safety.

Another challenge highlighted during the interview pertained to the interoperability and scalability associated with robotic adoption in the construction industry, particularly the necessity to address communication protocols, interfaces, standardized protocols, and guidelines to ensure seamless integration between robotic systems, humans, and construction equipment. Respondent 4 emphasized that.

> "*For robots to become more integrated, companies must develop open-source frameworks and industry standards consistent with facilitating collaboration, innovation, and interoperability across the robotic ecosystem and within the construction domain*." [R4]

Furthermore, a lack of funding from the government and attracting investment into robotic development and innovations in the construction sector in the UK continue to hinder their adoption and use. Additional issues revolve around significant intellectual property concerns, the risk of talent shortages, technological transfer without originality of design components, and the technical barriers associated with the language and coding of certain robotics that are not originally produced in the UK, thus posing technological differences.

While there were variations in the overall perception of robotics and its anticipated impact on construction in the UK, there was a shared recognition of its potential to shape trends and redefine narratives surrounding its adoption. Respondents agreed on the positive role of robotics and automation in enhancing various aspects of construction life, including design, implementation, safety, productivity, and efficiency. However, this optimism was contingent upon several factors that need to align or persist for meaningful transformation and widespread adoption of robotic technology in the UK. These include fostering interoperability and ensuring a conducive environment for large-scale adoption.

6.2 Survey Data

In addition to interviews, survey data were collected from several respondents using a semi-structured questionnaire structured with a Likert scale. The survey participants primarily consisted of industry experts from small to large construction companies with varying levels of experience and specialization across the United Kingdom. The data presented below represents the survey responses regarding the adoption of robotics and its efficacy in preventing construction injuries in the UK (refer to Appendix 1: Survey Questionnaire). A total of 54 valid questionnaires were collected, despite distributing over 150 questionnaires online and in person to ensure a robust dataset for addressing the research question. The questionnaire distribution spanned over six months, with an additional two-month follow-up period. This involved attending conferences, seminars, and workshops where construction stakeholders were present. Overall, the total number of responses was deemed sufficient for comprehensive data analysis.

The initial segment of the survey questionnaire focused on gathering demographic information from the respondents. Regarding years of experience, over 23% indicated having less than 5 years of experience in the construction sector. However, 47% reported having between 6 to 15 years of experience, signifying substantial expertise in the industry and progression over time. Additionally, 19% stated having 16 to 25 years of experience, while 11% had more than 25 years of experience in the construction field. These findings suggest that the respondents possessed considerable experience, likely providing them with valuable insights into the survey questions. Moreover, more than 77% of the respondents had over 6 years of experience. Respondents were asked about their professional background to ascertain the categories of their skills or expertise. Out of the total responses, 11% identified as Engineers, while 20% were involved in core construction roles.

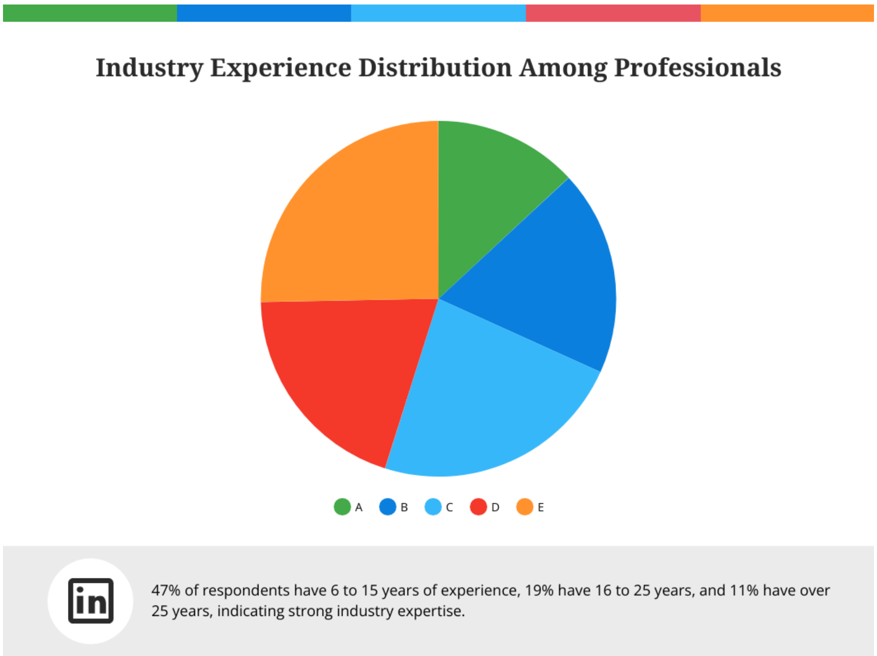

Figure 14: Industry Experience Distribution Among Professionals

Regarding the educational levels of the respondents, many indicated having significant educational backgrounds, with the minimum being a Diploma. None of the respondents reported having no formal education or only a high school level of education. This suggests a substantial educational foundation among the respondents, reflecting their knowledge and experience. Specifically, 11% reported having a Diploma or equivalent certificate, while 59% held a bachelor’s degree, indicating a strong knowledge base. Additionally, 20% possessed a master’s degree or equivalent postgraduate qualification, with the remaining 10% having other types of qualifications. Overall, the educational distribution of the respondents underscores their significant level of education.

The subsequent question addressed the size of the respondents' organizations. Many indicated affiliation with medium-sized organizations, although some mentioned working for small-sized ones. However, a notable proportion represented large organizations, as inferred from the average number of employees. Specifically, 27% reported working for small construction companies with 5-25 employees, while over 50% were from medium-sized organizations with 26-100 employees (54%). The remaining respondents (19%) were affiliated with large organizations. This diverse distribution across organization sizes provided a robust sample for assessing varying perspectives on robotics adoption and establishing the relationship between organizational size and the adoption of robotics.

Figure 15: Organisation Size Employee Distribution

The second section of the survey instrument aimed to assess the level of robotic technology utilization in the construction industry and the respondents' understanding of its applications and current state within the construction domain. Regarding the usage of robotic technologies, particularly exoskeleton arms, respondents provided varied responses ranging from high to unsure. A majority indicated a medium level of usage (39%), with 21% reporting high usage. The remaining responses were split between low (24%) and unsure (7%). Further analysis, correlating the usage of robotic arms with company size, revealed a positive correlation (+0.6%), suggesting that company size influenced the likelihood of adopting and utilizing robotic technologies. Overall, the data suggest that the level of robotic technology usage in the UK remains relatively low, with over 31% either unsure or reporting medium usage.

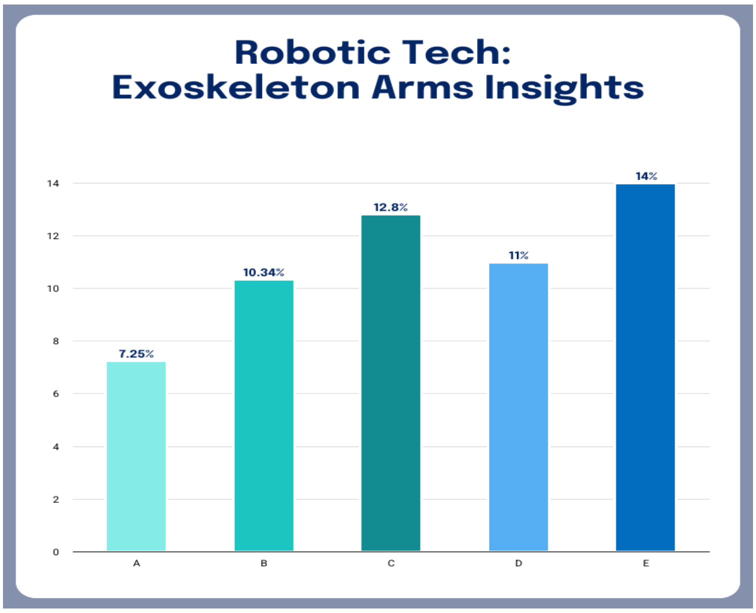

Figure 16: Robotic Tech: Exoskeleton Arms Insights

When asked about the potential of robotic technologies in preventing common construction-related injuries, near misses, and fatalities, respondents mostly indicated medium levels of usage in this regard. About 35% acknowledged the adoption of some robotic technologies on construction sites, while 19% recognized significant usage. However, the majority (46%) either expressed uncertainty or reported low utilization. A correlation analysis between these responses and company size revealed a positive correlation (0.62), suggesting that larger companies were more likely to adopt robotics on their construction sites.

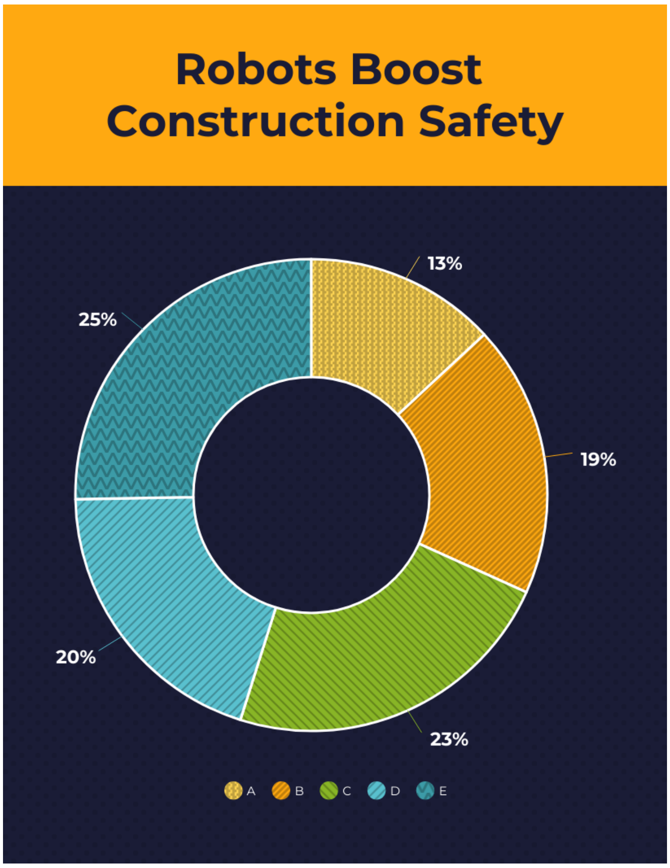

Figure 17: Robots Boost in Construction Safety

Respondents were queried about the extent to which robotics was employed to prevent common construction injuries, including near misses and the risk of fatalities. The responses presented a mixed aggregate, similar to the question concerning the level of robotic adoption on construction sites. A majority of respondents (33%) indicated a medium level of usage.

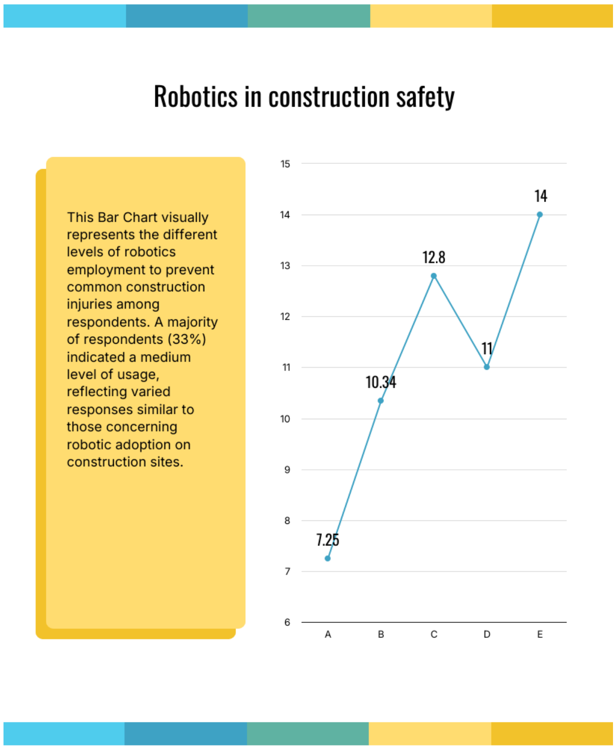

Figure 18: Robotic in Construction Safety

Five sets of questions were posed to address the limitations of robotic adoption in the UK construction industry. Regarding the question, "Do intellectual property issues about existing standards in the UK construction industry limit the uptake of robotic technologies?" half of the respondents (50%) either agreed or strongly agreed, while 39% disagreed or strongly disagreed. Meanwhile, 11% were unsure. These responses indicate a division among respondents on the significance of intellectual property rights as a barrier to robotic adoption in the industry.

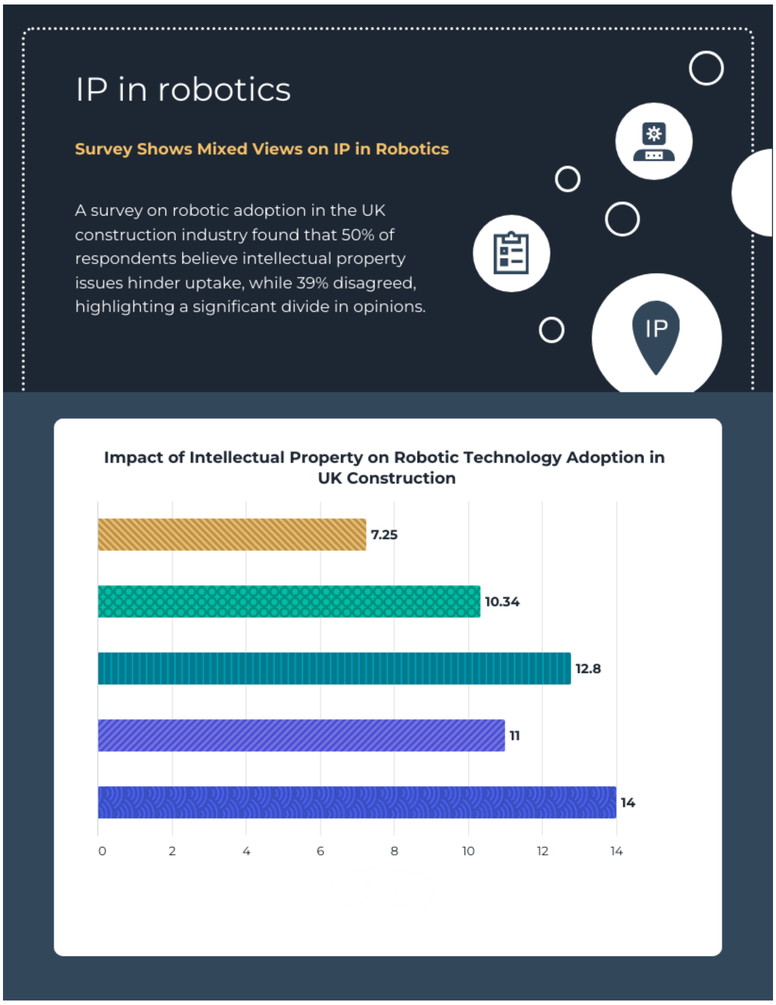

Figure 19: Impacts of Intellectual Property on Robotic Technology Adoption in UK Construction

When asked about institutional barriers, particularly the risk that robotics might replace workers in traditional construction roles, the responses painted a different picture. A significant majority, 65%, agreed that this was a substantial limitation. In contrast, 25% disagreed or strongly disagreed, and 10% were unsure about the impact of this factor on the adoption of robotics. These responses highlight that the perception of robotics as a threat to jobs and the traditional role of workers in construction is a central issue. This concern aligns with findings in the literature, which suggest that the economics of robotics and their impact on employment and conventional human labor are critical considerations (Xiang et al., 2021).

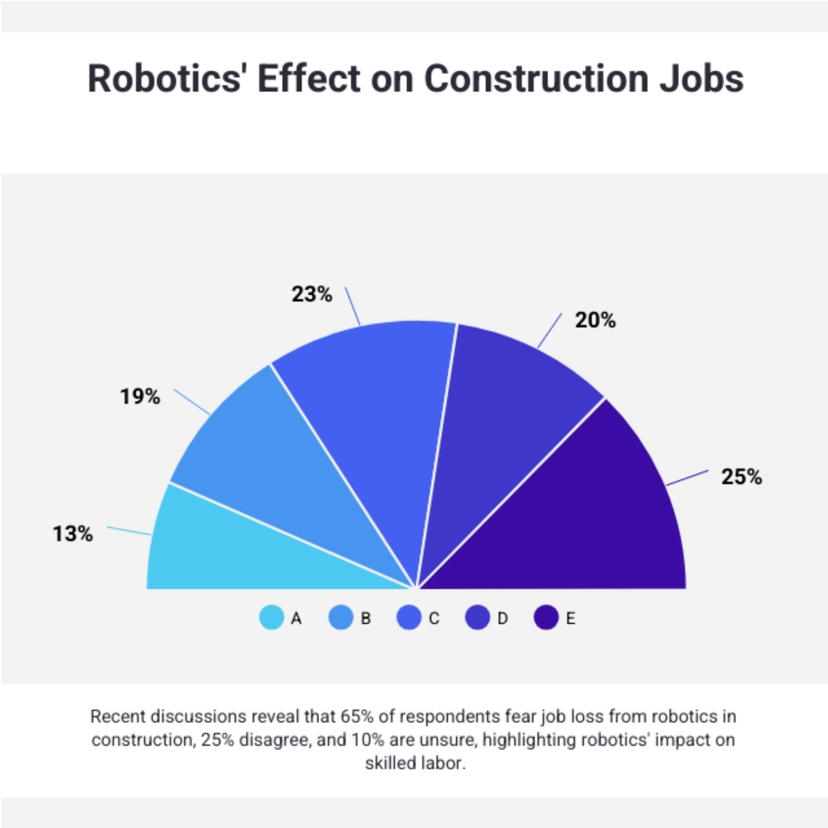

Figure 20: Robotics' Effect on Construction Jobs

When asked about their perception of the statement "Funding, research, and development indigenous to the UK is a significant factor affecting its adoption," the responses indicated a strong consensus. A significant majority, 78%, agreed or strongly agreed that this is a major consideration limiting the uptake of robotics. This aligns with the findings in the literature, which emphasize the need for improved research and development to incentivize robotic adoption in the UK construction industry. The remaining 22% of participants were either unsure or disagreed about the importance of funding in changing the adoption rate of robotics in the UK.

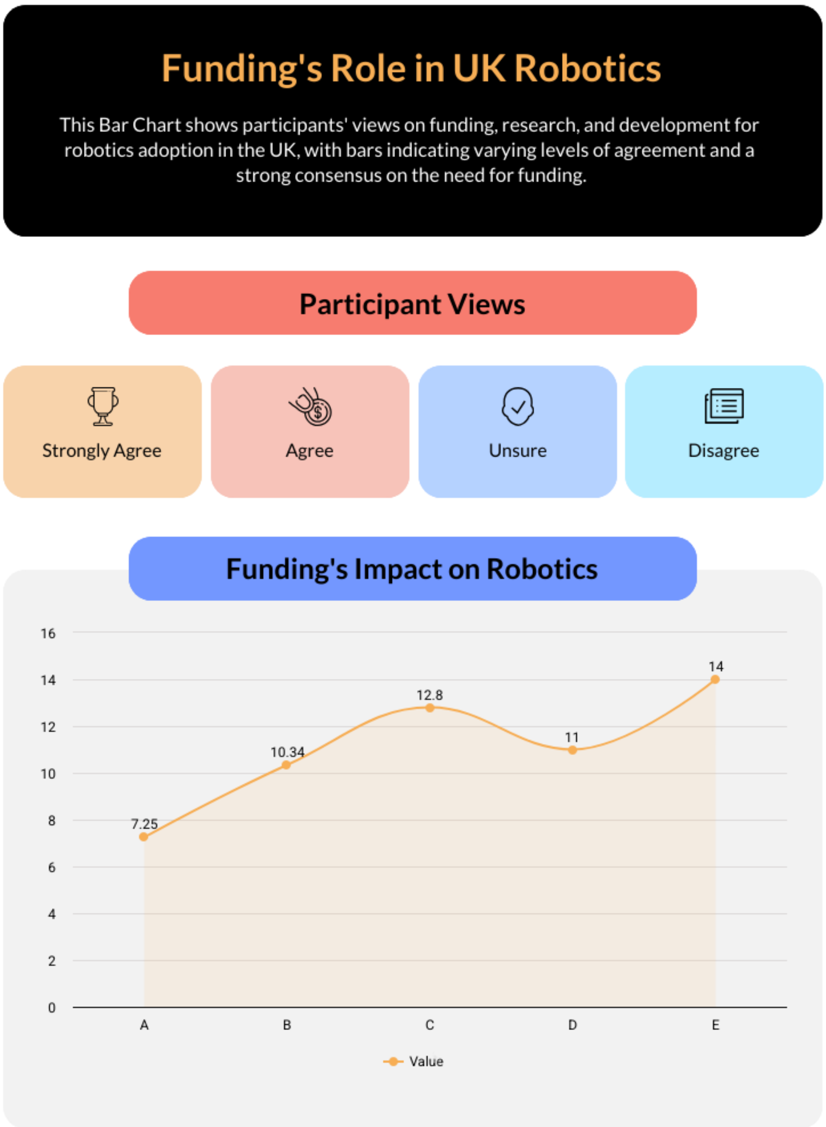

Figure 21: Funding's Impact on Robotics

Regarding the question "Is the cost of acquiring robots linked to its lower adoption rate?" respondents overwhelmingly affirmed that this was a major factor. An impressive 85% agreed that the high upfront costs of acquiring robotic and automation systems significantly impede their uptake, despite the benefits. This perspective is well-documented in the literature, which correlates the financial cost with the lag in acquiring the technology as a major factor limiting its adoption in the UK's construction industry.

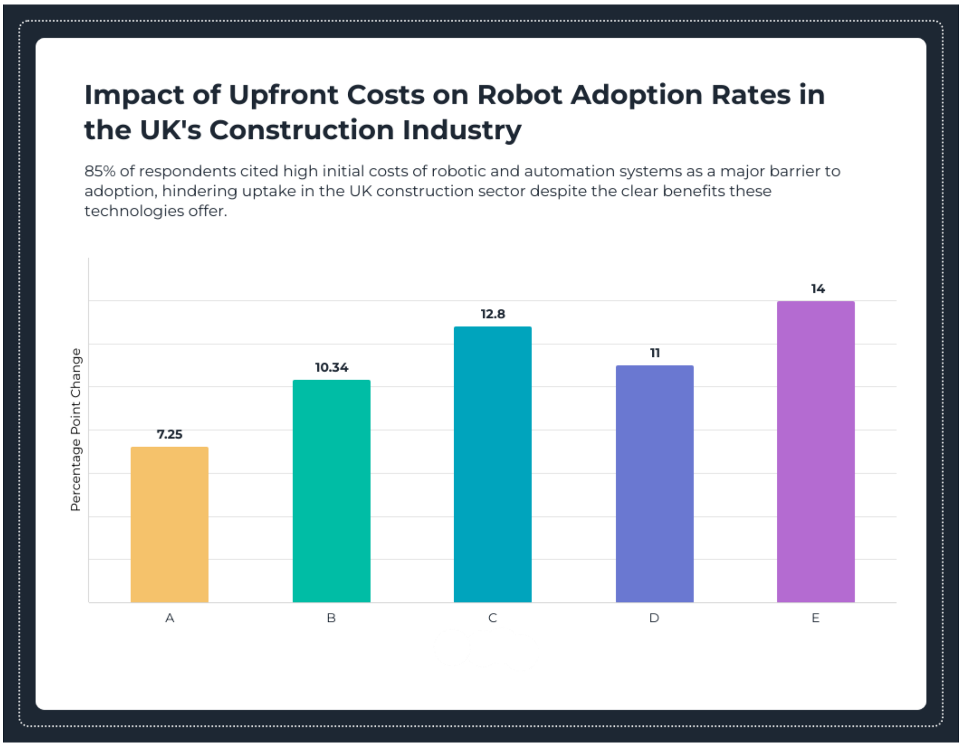

Figure 22: Impacts of Upfront Cost on Robot Adoption Rates in UK's Construction Industry

Another question addressed supply chain issues: "Supply chain issues and construction site analytics are critical factors affecting robotic technologies in the UK." The majority of respondents did not view this as a significant factor affecting their propensity to adopt the technology. Only 28% agreed or strongly agreed that this was a major consideration, while the majority, 72%, disagreed or were unsure about how much of an issue supply chain concerns were in their decision to adopt robotics.

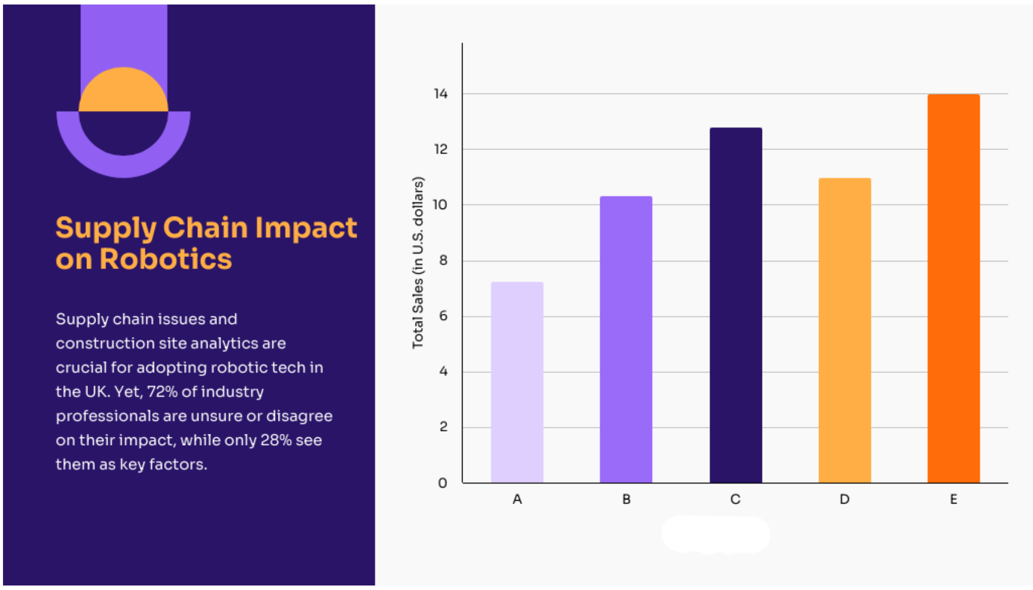

Figure 23: Supply Chain Impact on Robotics

Six questions were asked regarding the "Challenges of Robotics Adoption in the UK," and the responses revealed some interesting findings. When asked whether the "Cost implication for adopting, developing, and operationalizing its use affects its use in the UK construction sector," many respondents affirmed that this was a major challenge, particularly for small construction companies. These smaller companies often lack the resources to compete with larger firms that have more financial flexibility. A substantial 86% of respondents agreed or strongly agreed that cost was a significant barrier, while only 14% disagreed or were unsure. This result aligns with findings in the literature, which indicate that the high upfront costs associated with robotics are a significant barrier to adoption. This is a key issue that emerged from the literature review, highlighting how the cost implications shape the adoption of these technologies. The consensus among respondents reinforces the idea that cost is both a challenge and a barrier to the widespread adoption of robotics in the UK construction industry.

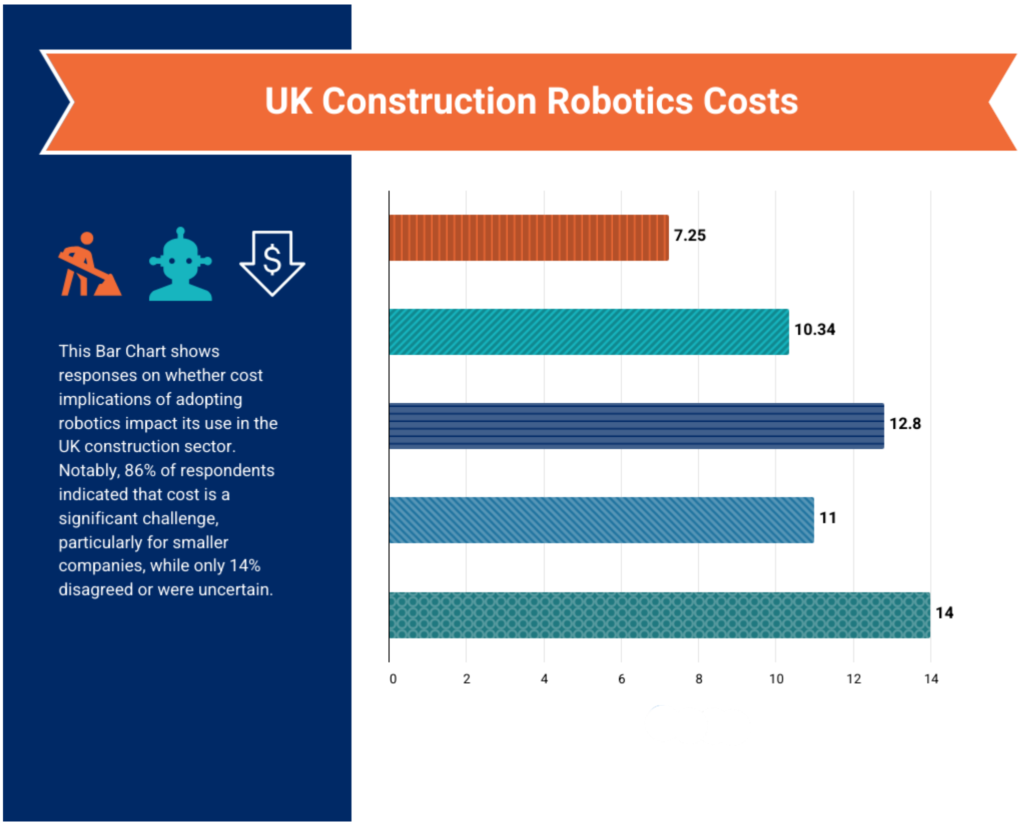

Figure 24: UK Construction Robotics Cost

When asked about the impact of usability and operability of robotics as a consideration challenging its use, a majority of respondents (52%) agreed or strongly agreed that this was a significant issue. However, 22% were unsure, and 26% disagreed or strongly disagreed, indicating a divided opinion on the matter. This aligns with findings in the literature, which identify usability and operability as main challenges impeding the adoption of robotics. The capacity of robots to function optimally in the construction industry—an environment known for its high risk and numerous hazards—remains a significant concern (Aghimien et al., 2019; Pan et al., 2020). Studies have also explored the intersection of operability and usability as a function of the robot's capacity to perform under various weather conditions. This ties into broader issues of trust and reliability, which are frequently raised in the literature as critical factors for the successful implementation of robotic systems (Pan et al., 2020b; Wang et al., 2020).

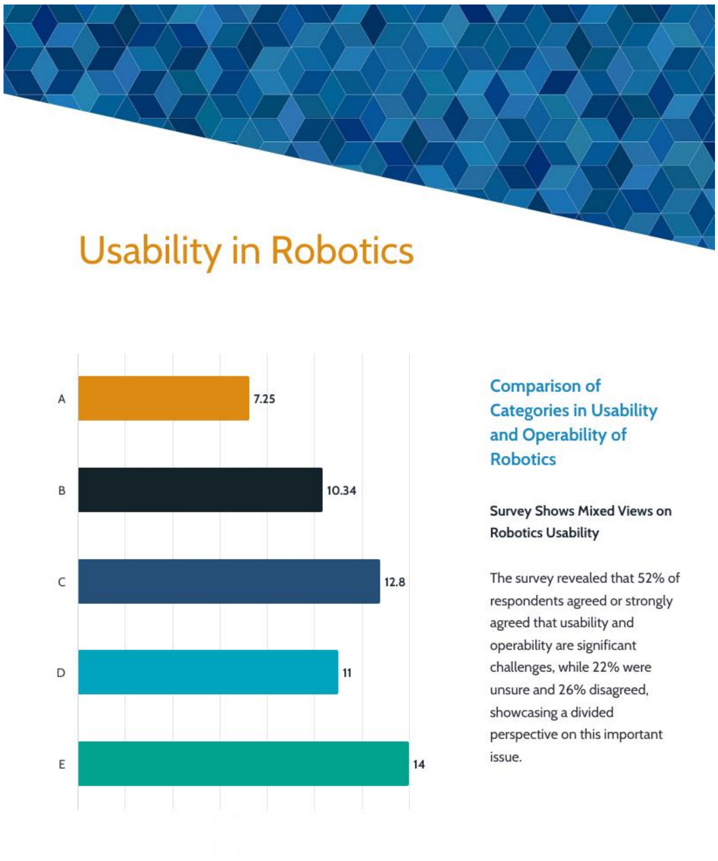

Figure 25: Usability in Robotics

The question of whether the "disruptive effects to traditional construction activities limit its use" significantly influences the perception and utilisation of robots in the construction industry was affirmed by the responses. A substantial 79% of respondents agreed that robotics is indeed disruptive, having a profound impact on conventional construction practices. This aligns with literature identifying employment impacts and the implications for skill development and the future of work as major concerns. The disruptive nature of robotics in the construction industry is seen as a shock factor, shaping the perception of its benefits.

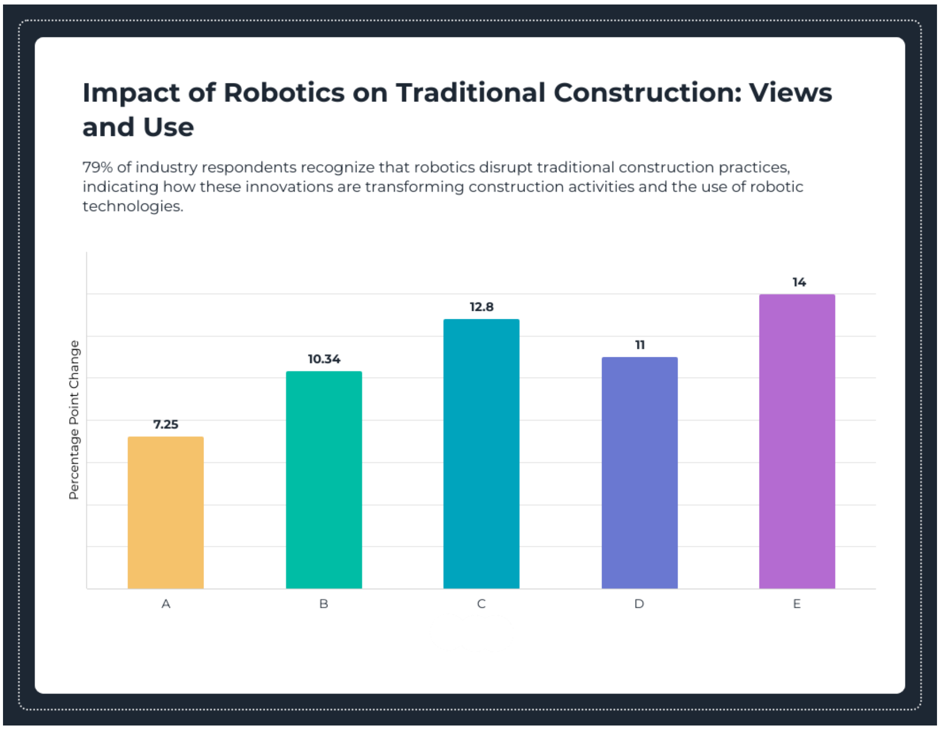

Figure 26: Impact of Robotics on Traditional Construction: Views and Use

Regarding the question of "technical skills and robots," responses were split. While 51% agreed or strongly agreed that technical skills are a significant factor, the remaining respondents were either unsure or disagreed to some extent. This indicates a recognition within the industry that upskilling, reskilling, and training are integral to integrating robotics effectively. The literature supports this, noting that robots are learnable (Xu et al., 2021). However, it also underscores that operating a robot requires specialized technical skills and expertise, which can be a barrier to adoption. This split response highlights the dual nature of the challenge: while robots are seen as a solution to improve safety and efficiency, they also necessitate a workforce proficient in new technologies, explaining the divided opinions.

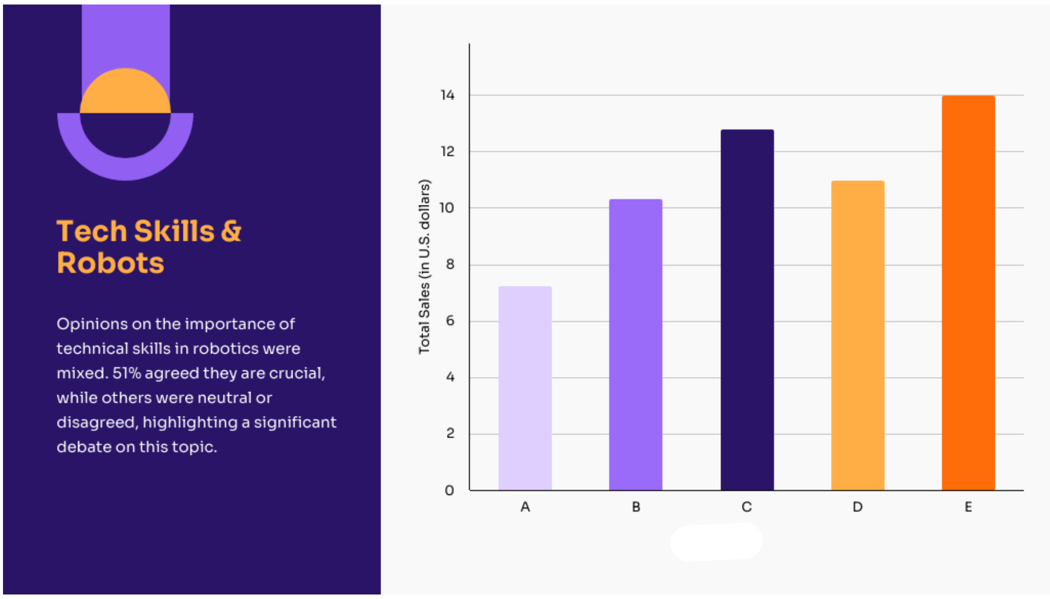

Figure 27: Tech Skills and Robots

Regarding the role of construction stakeholders in influencing the decision to adopt or not adopt robotics, most respondents agreed that this was a key and decisive factor shaping the deployment of robotics in the UK construction industry. An overwhelming 92% of respondents agreed that construction stakeholders played a major role in this process, while only 2% were unsure, and the remaining either disagreed or agreed to a lesser extent. This indicates that stakeholder influence is a significant factor in the consideration for adopting robotics, a point also acknowledged in the literature as a critical issue shaping the industry's adoption rate.

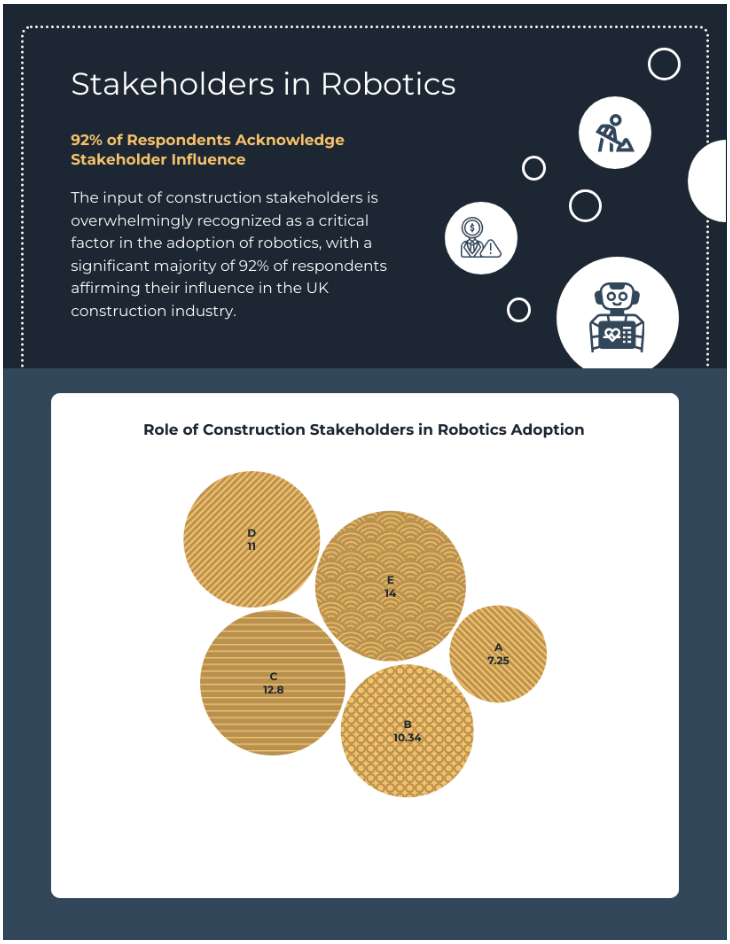

Figure 28: Stakeholders in Robotics

Another factor assessed was the role of "technical knowledge" as a push or pull factor impacting the industry's uptake of robotics. The data revealed that 58% of respondents agreed or strongly agreed that technical knowledge was a major consideration in determining robotic adoption. The remaining respondents were either unsure or disagreed.

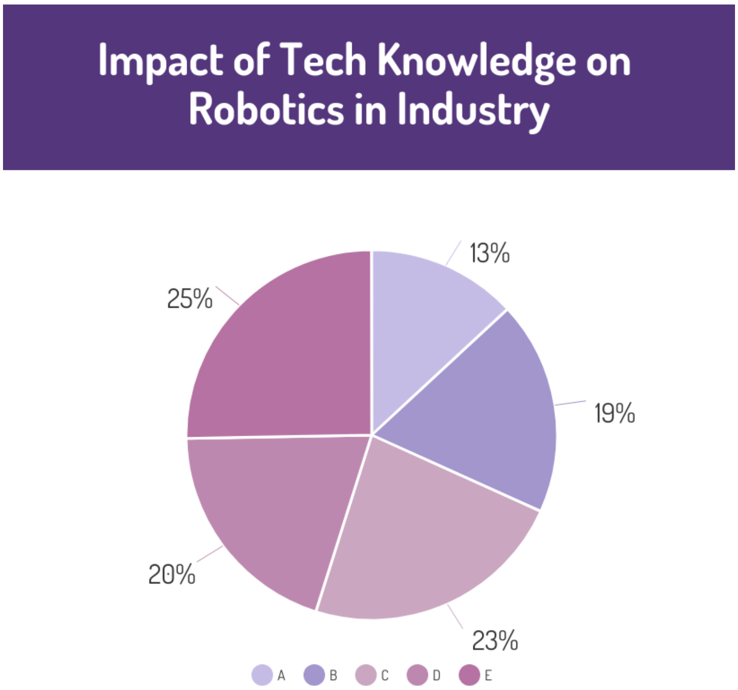

Figure 29: Impact of Tech Knowledge on Robotics in Industry

This finding is analogous to the literature, which indicates that post-Brexit, the UK has faced challenges, including the outflow of skills and expertise. Additionally, the aging population of the UK's labour force is another significant factor influencing the adoption of robotics, as it underscores the need for a technically proficient workforce to manage and operate new robotic systems.

Discussion

The construction industry is inherently hazardous, with workers exposed to various risks and dangers daily. Workplace injuries not only pose a significant threat to the health and safety of construction workers but also result in substantial financial costs and productivity losses for construction companies. In recent years, there has been a growing emphasis on leveraging robotic technology to mitigate these risks and enhance safety measures on construction sites. This discussion delves into the spate of robotic technology in preventing workplace injuries in construction, incorporating insights from industry respondents, relevant data, and statistical analysis to provide a comprehensive understanding of the topic. Before delving into the role of robotic technology in injury prevention, it is essential to understand the prevalence and nature of workplace injuries in the construction industry.

According to the HSE, the construction sector accounts for a significant proportion of workplace fatalities and injuries in the UK, with falls from height, being struck by moving objects, and slips, trips, and falls being among the most common causes of accidents. Statistics from the HSE reveal that in 2020/21, there were 37 fatal injuries and 54,000 non-fatal injuries reported in the construction industry in the UK alone. Robotic technology holds immense promise in addressing the root causes of workplace injuries in construction and enhancing safety measures on construction sites (Moore et al, 2021). Respondents from the construction industry emphasized the potential of robotics in automating hazardous tasks, reducing worker exposure to dangerous environments, and enhancing overall safety protocols. Robotic systems equipped with advanced sensors, cameras, and artificial intelligence algorithms can detect potential hazards in real-time, alert workers to imminent dangers, and even intervene to prevent accidents from occurring (Alma et al, 2019; Mahmood et al, 2022). For example, robotic exoskeletons have emerged as a promising solution for reducing musculoskeletal injuries among construction workers. These wearable devices provide ergonomic support and assistive capabilities, allowing workers to lift heavy objects with reduced strain and exertion. Research conducted by the Institute for Work & Health (IWH, 2022) found that the use of exoskeletons in construction resulted in a 20-30% reduction in the risk of lower back injuries, demonstrating the potential impact of robotic technology on injury prevention.

Furthermore, drones equipped with cameras and sensors have revolutionized safety inspections on construction sites, enabling aerial surveillance and monitoring of potential hazards from a safe distance. By conducting regular aerial surveys, drones can identify safety violations, structural defects, and other risks that may pose a threat to workers' safety. A study by Lee et al (2021) found that the use of drones for safety inspections led to a 50% reduction in the time required to complete inspections and a significant improvement in overall safety compliance. Despite the potential benefits of robotic technology in injury prevention, several challenges and barriers hinder its widespread adoption in the construction industry. Respondents cited cost as a major impediment, with the initial investment in robotic systems and technology often perceived as prohibitive for small and medium-sized construction companies. Additionally, concerns regarding the complexity of implementation, compatibility with existing workflows, and training requirements pose significant challenges for adoption (Wang et al, 2022; Sinclair et al, 2022). For example, robotic exoskeletons have emerged as a promising solution for reducing musculoskeletal injuries among construction workers. These wearable devices provide ergonomic support and assistive capabilities, allowing workers to lift heavy objects with reduced strain and exertion. Research conducted by the Institute for Work & Health (IWH, 2022) found that the use of exoskeletons in construction resulted in a 20-30% reduction in the risk of lower back injuries, demonstrating the potential impact of robotic technology on injury prevention.

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Moreover, regulatory constraints and safety standards may limit the deployment of robotic technology in construction, requiring companies to navigate a complex regulatory landscape to ensure compliance with health and safety regulations. The lack of standardized protocols and guidelines for the integration of robotic systems into construction workflows further complicates the adoption process, leading to uncertainty and hesitation among industry stakeholders. The spate of robotic technology in the prevention of workplace injuries in construction represents a significant step forward in enhancing safety measures and mitigating risks on construction sites. By leveraging advanced robotics, wearable devices, and unmanned aerial systems, construction companies can create safer work environments, reduce the incidence of workplace injuries, and improve overall productivity and efficiency. However, addressing the challenges and barriers to adoption, such as cost, complexity, and regulatory constraints, will be crucial to unlocking the full potential of robotic technology in injury prevention. Collaborative efforts between industry stakeholders, regulatory agencies, and technology providers will be essential in driving innovation, fostering adoption, and promoting the widespread implementation of robotic solutions in the construction industry.

Respondents were asked a series of questions, and their answers were analysed. It is evident from the responses that a significant majority (70%) either strongly agreed or agreed that the implementation of robotic technology is costly compared to traditional methods. Similarly, 73% of respondents expressed strong agreement or agreement that the technical knowledge required for implementing robotic technology in the UK construction sector poses a major barrier. Furthermore, 70% of participants acknowledged the limited government policy incentives for robotic technology adoption in the construction industry, while 30% either disagreed or were unsure. Regarding guidance on the operational aspects of robotic technology, 76% of respondents indicated a shortage in the UK construction sector, with 24% expressing uncertainty. Additionally, 71% of participants agreed or strongly agreed that a passive culture regarding the utility of robotic technology makes its implementation impractical, while 29% were unsure. Regarding infrastructural challenges and political factors, 73% of respondents affirmed these as major threats to robotic technology adoption, while 27% were unsure. Similarly, 72% agreed that the centralized nature of procurement in the UK public sector hampers the adoption of innovative procurement methods, with 28% expressing uncertainty. A comprehensive analysis of these percentages suggests that while there is potential for the operationalization of robotic technology in the UK construction sector, various barriers hinder its widespread adoption.

The construction industry in the UK is on the cusp of a transformative shift, propelled by the advent of emerging robotic technologies. These innovations, ranging from autonomous drones to unmanned ground vehicles and robotic exoskeletons, offer unprecedented opportunities to enhance construction prevention measures. By automating tasks traditionally associated with safety hazards, repetitive labour, and meticulous monitoring, robotic systems have the potential to revolutionize safety practices in construction. However, the journey towards widespread adoption of robotic technology in construction prevention is not without its challenges. While there is growing recognition of the importance of safety within the industry, significant barriers hinder the uptake of robotic solutions. High initial costs, technological complexity, regulatory constraints, and concerns about return on investment pose formidable obstacles for construction companies considering the integration of robotic systems into their operations. Despite these challenges, there is a palpable sense of optimism among industry stakeholders regarding the prospects of adopting emerging robotic technology in construction prevention. Interviews and surveys with construction managers, health and safety officers, and other key players reveal a shared belief in the potential of robotics to mitigate safety risks and improve overall project outcomes. However, practical considerations such as ease of use, customization options, and seamless integration with existing workflows are paramount for successful adoption.

To overcome barriers to adoption and maximize the benefits of robotic technology in construction prevention, several key considerations must be addressed. Firstly, cost-effectiveness is crucial – robotic solutions must demonstrate tangible economic benefits, such as reduced accident rates, insurance premiums, and project downtime, to justify their upfront investment costs. Secondly, a robust regulatory framework is essential to ensure safety, reliability, and legal compliance in the deployment and operation of robotic systems on construction sites (Nagara et al, 2020; Finbar et al, 2021). Furthermore, efforts to upskill the construction workforce and increase awareness of emerging robotic technologies through training programs, workshops, and industry partnerships are imperative. Collaboration between stakeholders – including government agencies, academia, industry associations, and technology providers – is essential to drive innovation, share best practices, and address common challenges collectively.

Four sets of questions were posed, and the responses were subsequently analyzed. It is clear from the responses that the majority of respondents (75%) affirmed that "Adopting robotic technology in the UK construction industry poses significant challenges." Similarly, 82% of respondents expressed strong agreement or agreement that robotic technology adoption has the potential to revolutionize construction practices and increase efficiency. Regarding the economic benefits of adopting robotic technology, 74% of participants affirmed this statement, while 26% either disagreed or were unsure. When asked whether the UK construction industry would benefit significantly from robotic technology adoption on a national scale, 72% of respondents considered this statement to be correct, although 30% were unsure or undecided. A detailed analysis of the respective percentages for each statement reveals that respondents, who are experts in construction and engineering, acknowledge the challenges associated with adopting robotic technology in the UK construction industry, despite recognizing its potential to revolutionize construction practices and enhance efficiency.

The first objective of this research was to delve into the main factors influencing the development and adoption of robotic technology within the building construction sector in the UK. To achieve this, a comprehensive approach was undertaken, involving a mix of qualitative and quantitative methods. Qualitative research methods included conducting in-depth interviews with key stakeholders in the UK construction industry. These interviews involved experts from various domains, including robotics engineering, construction management, digital technologies, and regulatory bodies. Through these interviews, insights were gathered regarding the current state of robotic technology adoption, the challenges faced, and the potential future trajectory.

Additionally, an extensive literature review was conducted to gain a comprehensive understanding of the existing research on robotic technology adoption in the construction industry globally, with a specific focus on studies related to the UK context. This literature review helped identify key themes, trends, and factors influencing robotic technology development and uptake in building construction. Quantitative research methods were employed to complement the qualitative findings. Surveys were distributed among construction industry professionals, including contractors, architects, engineers, and robotic technology suppliers. These surveys aimed to collect data on the current level of robotic technology adoption, perceived benefits and barriers, and future expectations. By triangulating data from qualitative interviews, literature review, and quantitative surveys, a holistic picture of the factors shaping robotic technology development and uptake in the UK building construction industry was obtained. Factors such as technological advancements, regulatory frameworks, industry culture, economic incentives, and workforce readiness were identified as key influencers in this regard.

The second objective of the research was to identify the primary factors hindering the adoption of robotics in building construction within the UK. This objective aimed to provide insight into the specific challenges that need to be addressed to facilitate greater adoption of robotic technology in the industry. To accomplish this objective, a structured approach was adopted, involving both qualitative and quantitative analyses. Qualitative data collection methods included interviews with industry experts, focus group discussions, and case studies of companies that have attempted to integrate robotics into their construction processes. Through these methods, a wide range of barriers to robotics adoption were identified, including cost constraints, technological complexity, regulatory hurdles, a lack of skilled workforce, and cultural resistance to change. Following the qualitative data collection phase, a thematic analysis was conducted to categorize the identified barriers into distinct themes or categories. This process helped in organizing the data and identifying common patterns across different barriers. Quantitative data analysis involved ranking the identified barriers based on their perceived significance and impact on robotics adoption in building construction. Surveys were distributed among a diverse range of construction industry stakeholders, asking them to rate the importance of various barriers on a Likert scale. By combining qualitative insights with quantitative data analysis, a comprehensive understanding of the main factors limiting robotics adoption in building construction in the UK was achieved. This information provided valuable insights for policymakers, industry leaders, and technology developers to prioritize interventions and strategies aimed at overcoming these barriers.

The third objective of the research was to explore potential strategies and interventions to enhance the adoption of robotic technology in the UK construction industry. This objective aimed to provide actionable recommendations for stakeholders looking to promote the uptake of robotics in building construction. To address this objective, a multi-faceted approach was adopted, involving a combination of desk research, stakeholder consultations, and expert workshops. Desk research involved reviewing existing literature on best practices and success stories related to robotics adoption in construction industries around the world. Case studies of companies that have successfully implemented robotics in their construction processes were analysed to extract valuable lessons and insights. Stakeholder consultations were conducted through interviews, focus groups, and surveys to gather input from industry practitioners, technology developers, policymakers, and other relevant stakeholders. These consultations helped identify potential barriers and opportunities for robotics adoption in the UK construction industry, as well as innovative solutions and strategies to address them. Expert workshops were organized to bring together key stakeholders and experts in robotics, construction, and related fields to brainstorm ideas and develop actionable recommendations. These workshops facilitated knowledge exchange, collaboration, and consensus-building among participants. Through a process of iterative analysis and synthesis, a set of actionable recommendations and strategies was developed to improve robotic technology adoption in the UK construction industry. These recommendations covered a wide range of areas, including policy and regulatory reforms, financial incentives, education and training programs, industry collaborations, and technology innovation initiatives.

The fourth objective of the research was to propose a comprehensive framework for the adoption of new and emerging construction technologies in the UK. Building upon the findings from the previous objectives, this framework aimed to provide a structured approach for stakeholders to navigate the complexities of technology adoption in the construction industry. The development of this framework involved synthesizing insights and best practices from the research conducted under the first three objectives, as well as drawing upon relevant literature and industry standards. This involved evaluating the readiness of new and emerging construction technologies, including robotics, for adoption in the UK context. Factors such as technological maturity, cost-effectiveness, scalability, and compatibility with existing processes were considered in this assessment. The framework outlined the roles and responsibilities of various stakeholders involved in the technology adoption process, including policymakers, industry associations, technology developers, construction companies, research institutions, and training providers.

Based on the identified barriers and opportunities, the framework proposed tailored implementation strategies to address specific challenges and facilitate the uptake of new technologies. These strategies encompassed policy reforms, financial incentives, capacity-building initiatives, industry collaborations, and technology demonstration projects. The framework included provisions for ongoing monitoring and evaluation of technology adoption efforts to track progress, identify bottlenecks, and make necessary adjustments. Key performance indicators and benchmarks were defined to measure the success of technology adoption initiatives over time. By providing a structured roadmap for technology adoption, the proposed framework aimed to empower stakeholders to navigate the complexities of introducing new and emerging construction technologies into the UK market. This framework served as a valuable tool for guiding decision-making, resource allocation, and collaborative action towards realizing the full potential of robotics and other innovative technologies in the construction industry.

In practical terms, the fundamental components of construction can be broken down into parts and connectors, like bricks and cement, wooden slabs and mating joints, or girders and bolts. This decomposition allows for construction activities to be methodically deconstructed into a series of assembly operations, gradually forming larger assemblies from individual parts. Over recent decades, the concept of prefabrication, which involves manufacturing the majority of a building's sub-assemblies in a controlled factory environment before transporting them to the construction site for assembly, has gained traction in the construction industry. This trend is exemplified by the rise of modular buildings and homes, which are gaining popularity due to their efficient use of prefabricated components.

Compared to traditional site-cast construction methods, prefabricated elements offer numerous advantages, including faster production, lower costs, and more efficient assembly. For instance, replacing in-situ concrete casting with prefabricated elements has been shown to reduce construction time by up to 70% and labor costs by 43% (Brilakis et al, 2021). Additionally, prefabrication promotes a cleaner and safer construction environment. Despite these benefits, off-site construction methods, including prefabrication, account for only a small fraction (around 10%) of the UK construction market (Kasperkzsky et al, 2021). This slow adoption can be attributed to various technical, financial, and regulatory barriers. One of the most significant challenges is the perceived inflexibility of prefabrication in accommodating changes in design, which is a prevalent concern within the industry.

To address this challenge, the construction industry has embraced the concept of mass customization, aiming to increase flexibility by offering a range of customizable modules based on standardized core designs (Bambor et al, 2019; Zhang et al, 2021). However, achieving mass customization requires a high level of automation to streamline the production process and accommodate design changes efficiently. This need for automation and mass customization has spurred developments in the field of 'robotic prefabrication.' In industries such as precast concrete, robotics has been successfully employed to automate various tasks, from setting molds to placing reinforcement bars, enhancing flexibility in the production process.

While robotic fabrication has improved flexibility during the design process, incorporating changes after physical construction remains a challenge. This limitation highlights the need for further innovation, particularly in the realm of automated disassembly and reconstruction, or "refabrication." A solution to the inflexibility associated with prefabrication and automation would not only accentuate the benefits of prefabrication over traditional construction but also enhance productivity levels. Studies (Green et al, 2018; Shoudary et al, 2018) have shown that a significant portion of construction projects (approximately 40%) experience changes during execution, and productivity tends to decrease when changes are not effectively managed (Siegel et al, 2020). Automated refabrication can address design changes promptly and effectively, thereby improving productivity and reducing waste. Moreover, automated refabrication aligns with the principles of sustainable construction by enabling the reuse of components and resources.

In situations where design changes or inspection failures occur, modifying the original structure through automated disassembly and refabrication is less wasteful than complete demolition and reconstruction.

CHAPTER SEVEN: Conclusion, Recommendations, Proposed Roadmap

7.0 Conclusion

The thesis commenced with a set of research objectives aimed at comprehensively examining various aspects related to the integration of robotic technology in the construction industry within the UK. Firstly, it sought to conduct a thorough analysis of the current state of construction practices in the UK to determine the extent of preparedness for the adoption of robotic technology. Secondly, it aimed to evaluate the utilization of robotic technology in mitigating construction-related injuries and reducing health and safety risks in the construction sector. Thirdly, the research aimed to identify and assess the factors that may hinder the widespread adoption of robotic technology in the UK construction industry. Lastly, it sought to explore potential strategies and interventions to enhance the adoption of robotic technology for preventing construction injuries.

To address the first objective, the research aimed to thoroughly assess the readiness of the construction ecosystem in the UK concerning the adoption of technology, specifically robotics. This involved conducting a comprehensive literature review to gather insights from existing studies and obtaining perspectives from various stakeholders within the construction industry. Upon reviewing the literature, a significant observation emerged: while the UK has demonstrated notable progress in embracing technology across various sectors such as AI, machine learning, drones, and big data in healthcare, agriculture, hospitality, manufacturing, and industry, the construction sector lags in the adoption of robotics (Reeds et al, 2021; Gleeds et al, 2022).

The thesis identified a conspicuous absence of robust regulatory frameworks, which serve as crucial catalysts for expediting the adoption of robotics within the construction industry. Several factors, including the intricacy of construction projects, the need for a conducive environment, upfront costs, technological hurdles, research and development constraints, and essential investments in robotics and scalability, emerged as recurring challenges (Wu et al, 2020; Lin et al, 2022; McCormick et al, 2022). These challenges, compounded by other macro-level variables such as Brexit and post-pandemic disruptions following Covid-19, underscore the pressing need for substantial interventions within the construction sector. Moreover, the UK construction industry grapples with an aging workforce, a demographic trend that exacerbates susceptibility to diseases due to age-related decline (Maartens et al, 2019; Sinclair et al, 2018).

This aligns with existing data that underscores the correlation between age and susceptibility to injuries (Wang et al, 2021). Moreover, while the age-related challenge persists, particularly in the context of Brexit's transformative impact, the UK is witnessing a resurgence in efforts to automate the construction sector, albeit lagging behind other OECD and Western nations in terms of adoption, integration, and utilization. However, the transition to robotics, as evidenced by this study, is contingent upon several pivotal factors specific to operationalizing such advancements in the UK. These factors encompass stakeholders' perceptions and concerns regarding sustainable construction, which have emerged as focal points in the deployment of robotics, particularly to align with the UK's ambitious goal of achieving carbon neutrality by 2050.

However, despite significant government announcements and policy plans aimed at revitalizing the construction sector, many of these initiatives are futuristic and fall within mid to long-term timelines for implementation. Nevertheless, there is a growing sentiment among major construction stakeholders regarding the adoption of robotics. Key respondents interviewed for this study expressed acknowledgment of the gradual uptake of robotics, attributing it to factors such as the time required for adoption, the need for skills and training, and the complexity of various construction tasks that may necessitate the use of multiple robotics systems. However, the overall attitude and perception towards robotics indicate an inevitable innovation that the construction industry must embrace, particularly in preventing injuries and mitigating the risks of fatalities associated with high-risk and repetitive tasks.

This assessment occurred within the context of recognizing the various benefits of robotics. However, it was also acknowledged that the UK construction industry must adopt a realistic approach to operationalizing robotics amidst the evolving landscape of human-machine collaboration and the emerging challenges of cybersecurity and data security. Access, equity, and availability emerged as critical factors in the adoption of robotics. Stakeholders highlighted that while the UK construction industry is a significant employer and contributor to the country's GDP, the accessibility of these technologies, defined by their socialization or potential for mass production, is crucial in bridging the gap between large and small companies in accessing these transformative technologies.

This is compounded by the fact that many of these robotic technologies are still in their infancy and have not undergone extensive testing on a large scale or in commercial settings. There are concerns that newer innovations may require further adaptation and adjustments to meet the competitive demands of the market (economies of scale). Furthermore, there are equity issues surrounding how these technologies bridge the gap in terms of accessibility, usability, and the extent to which they become normalized as customary practices, as dictated by existing regulations governing their use. Adding to these challenges is the fact that some specifications for these robotic technologies are imported from overseas, potentially leading to a reliance on foreign expertise for ongoing maintenance and support. This introduces a geopolitical dimension to the issue of robotic adoption within the broader context of globalization. However, the focus on availability highlights the importance of ensuring that these technologies are accessible for purchase at a price point that encourages widespread adoption.

7.1 Paradox of robotic adoption and construction injuries

This thesis delved into the examination of robotics adoption within the UK construction sector, a pivotal aspect of its investigation. To achieve this objective, a multifaceted approach was employed, combining interviews, surveys, and a comprehensive literature review to distill insights. Various theories of robotic adoption, including the Diffusion of Innovations (DOI) theory, were explored to ascertain the current position of the robotic value chain within the UK context. DOI theory delineates the process of technology adoption into five stages, beginning with knowledge acquisition, where individuals become aware of new technologies. Subsequently, the persuasion stage involves convincing stakeholders of the benefits of these technologies and advocating for their adoption. The decision phase follows, focusing on the evaluation of technology use against its potential advantages and disadvantages.

This leads to the penultimate stages focused on implementation and confirmation of technology adoption (Lin et al., 2017). However, while the theory outlines a structured process, it does not offer a universal framework for the adoption pathway that organizations or stakeholders may follow. For instance, it overlooks the crucial aspect of social acceptance and public perception of construction products (Wien et al., 2017), which is central to the social cognitive theory. This theory elucidates how the adoption of new technology is influenced by observing and imitating others, as well as weighing the perceived benefits and costs (Alaiad, 2014; Henschel et al., 2020). Furthermore, it disregards the role of resources in technology adoption, a cornerstone of the resource-based view theory. This perspective posits that organizations with greater resources are more inclined to adopt new technology due to their capacity to invest in and effectively implement it (Pillai et al., 2020). While DOI does address the decision phase, it overlooks how these decisions are shaped by organizational and industrial norms, values, and regulatory frameworks (Gupta et al., 2020). Additionally, it fails to capture the nuances of the innovation ambition theory, which elucidates how organizations and individuals determine technology adoption. According to this theory, the adoption of new technology is driven by organizational and individual ambitions to innovate (Wood et al., 2017).

While DOI provides a valuable framework for understanding technology uptake, it has limitations in capturing the entirety of the adoption process. Nonetheless, it offers a crucial perspective for synthesizing and comprehending technology adoption trends. Building upon this, the thesis delineated three distinct phases of robotic adoption in the UK: the lag phase, acceleration phase, and steady phase, followed by the peak phase and a subsequent acceleration phase. Analysis revealed that the UK construction industry is positioned between the lag phase and a shift towards acceleration due to ongoing efforts to embrace robotics and invest in related research and development. However, the current landscape underscores a paradox concerning robotic adoption and construction-related injuries.

The paradox identified in this study stems from the stark contrast between the UK's potential as a leading technological nation and the persistent issue of construction-related injuries and fatalities. Despite advancements in robotics aimed at mitigating these safety concerns, reports from organizations such as HSE and OSHA indicate a continuous rise in such incidents. Insights gathered from interview respondents echo this sentiment, highlighting the UK's untapped potential to address and reduce these injuries. However, the primary limitation lies in the scalability of technology for construction companies and its practical application within varying contexts.

7.1.1 Prospects of Robotics

The investigation conducted in this thesis delved into the fundamental aspects of robotic adoption within the UK construction industry. Various robotic applications and innovations were identified and evaluated based on their functional benchmarks, capacity for human-robot collaboration, and their ability to achieve desired outcomes. Notably, it was found that approximately 90% of construction tasks involve manual handling, increasing the susceptibility of construction workers to Work-Related Musculoskeletal Disorders (WMSDs) and contributing to the incidence of construction-related injuries in the UK (Kaur et al., 2019). One key finding revealed a significant investment in research and development within the UK robotics sector. However, despite this progress, many of these innovations have yet to undergo significant commercial rollout due to limited laboratory testing facilities. Nevertheless, these advancements suggest promising returns, particularly when aligned with planned government initiatives aimed at incentivizing robotic innovations in the UK.

The exploration of robotic innovations aimed at preventing injuries predominantly focused on repetitive strain injuries and those resulting from overuse or overextension. Key insights gleaned from the study closely mirrored the perspectives shared by interview respondents regarding the potential benefits of robotics. Existing and emerging studies (Brock, 2003; Palikhe et al., 2020; Zhang et al., 2020b; Pan et al., 2020; Wang et al., 2021) have outlined numerous advantages associated with the adoption and utilization of robotics within the construction sector, including the mitigation of dangerous falls from heights, protection of craft workers from repetitive tasks, prevention of injuries to tendons and joints, thereby reducing the risk of MSDs, reduction of lifting-related fatigue, mitigation of health and safety hazards, lowering operational costs, enhancing productivity, and minimizing the risk of structural defects. Additionally, robotics offers applicability for surveillance functions in high-altitude environments and risky terrains unsuitable for human presence, while advanced robots equipped with AI and machine learning capabilities can operate autonomously and simulate potential risks and hazards (Zhou et al., 2019).

The study identified a wide array of robotic advancements geared towards injury prevention. Recent innovations in robotics boast varying degrees of autonomy, operating seamlessly in real-time without human intervention, thanks to pre-programmed algorithms (Walsh et al., 2017). This autonomy enables robots to execute tasks, make decisions, and devise solutions independently, rendering them invaluable in dynamic, unstructured, and complex work environments fraught with potential hazards. Moreover, robots play a crucial role in mitigating the risk of sprains, strains, and MSDs associated with repetitive and monotonous tasks. For instance, the Toyota KAIST HUBO-FX1 mobility robot, wearable as a mobile suit, enhances lifting capacity and muscle usage while introducing new capabilities for task performance (Liu and Li, 2018). A South Korean iteration of this robot has been specifically designed and commercialized to prevent knee impairments and aid in maintaining balance while lifting heavy materials. Despite their promise, many existing robotic models originate from overseas, predominantly Asia and Europe. This highlights a significant reliance on imported robotics in the UK, underscoring the nascent state of indigenous robotic development. Echoing the sentiments of interviewees, there is a pressing need for increased research and investment in robotics to foster local manufacturing and widespread adoption on a larger scale.

The final chapter of this thesis critically reappraises the evidence and reiterates the arguments made throughout regarding the adoption of robotics in preventing construction injuries and improving health and safety in the UK construction industry. The central argument acknowledges that despite the recognized utility of robotics in enhancing productivity, efficiency, and safety, their uptake in the UK construction sector remains slow due to a plethora of factors, including economic, political, cultural, perceptual, and technological issues.

The chapter concludes that while the prospects for robotics in preventing construction injuries and improving health and safety are promising, numerous barriers impede their widespread adoption. These conclusions are supported by both survey and interview data from research respondents, highlighting the multifaceted challenges and potential of robotics within the industry.

However, the impediments faced by the adoption of robotics in the UK construction industry remain rooted in the same core reasons that have historically hindered technological adoption. The double helix impact shows that while there is a significant appetite for robotics in the UK, uptake is primarily driven by a cost-benefit analysis. This analysis assesses how these robots meet the critical and evolving needs of the industry without compromising profitability. The gaps identified through this research formed the basis for the recommendations put forward in this thesis. These recommendations stemmed mainly from the gaps identified in the literature review and the unaddressed needs highlighted during the study.

7.2 Recommendations

Through the examination of research findings, several gaps have been identified that affect the adoption of robotics in the UK construction sector for injury prevention and overall enhancement of health and safety standards. While there exists a generally positive momentum toward robotics implementation, numerous factors hinder its widespread adoption in the UK construction industry. This section delineates recommendations aimed at optimizing, incentivizing, and increasing the adoption of robotics to prevent construction injuries and enhance overall health and safety protocols in the construction sector.

Table 7: Summarising key recommendations

Streamlining Research and Development Funding for Robotics in the UK	- Establish a dedicated funding pipeline for robotics R&D in construction. - Focus on industry-relevant research, including robotics showcases and educational initiatives. - Increase investment in MSc and PhD research to address health and safety challenges. - Promote partnerships between government, academia, and industry to foster innovation.
Encouraging Domestic Production of Robots	- Incentivize local robot production for construction through tax rebates and government intervention. - Prioritize localized innovations to enhance construction sector growth and efficiency. - Promote cleaner methods of production, such as re-melting steel scrap for robotics manufacturing. - Encourage small industries to experiment with robotics before scaling up.
Saliency of Roadmap for Robotic Adoption	- Develop a comprehensive 5+ year roadmap for robotic adoption in construction. - Include clear, measurable objectives for robotics development and integration. - Address talent gaps and provide interventions to ensure successful adoption. - Align robotic adoption with commercial, industrial, and environmental requirements.
Upskilling Programmes to Address Skill Shortages	- Update the UK curriculum to include robotics and STEM innovations. - Promote work-integrated learning to bridge industry-academic gaps. - Offer incentives to attract talent in robotics and STEM fields. - Develop specialized apprenticeships and degree programs to address skill shortages in construction robotics. - Facilitate knowledge transfer from other countries with advanced robotics adoption.
Addressing Investment Disparities in Robotics	- The UK construction sector receives less than 1.5% of the total UK investment in robotics. - The majority of investment goes to automotive, manufacturing, and healthcare. - Construction sector underinvestment hinders robotics adoption. - Robotics investment could significantly enhance construction sector productivity. - Need to align investment with industry appetite and government policies.
Addressing Upfront Costs: Policy Incentives	- Upfront costs are a major barrier to adopting robotics. - Small businesses struggle with the installation and adoption costs. - Policy incentives such as subsidies, tax incentives, or

	grants are needed. - Accessibility and equity are key to making robotics available to all stakeholders. - Government intervention can help level the playing field for smaller companies.
Enhancing Health and Safety through Collaboration	- Collaboration between construction industry stakeholders and regulatory agencies is essential to improve safety. - Develop specific health and safety standards for robotics in construction. - Robotics should be designed to minimize injuries and align with safety specifications.
Raising Public Awareness: Shifting Perceptions of Robotics	- Public perception often fears job loss due to robotics adoption. - Awareness workshops and educational campaigns can help shift perceptions. - Providing upskilling opportunities will increase workers' comfort with new technologies. - Gradual integration of robotics will help build trust and acceptance. - Emphasize the sustainability and scalability of robotics in construction.
Addressing Core Barriers to Robotic Adoption	- High costs, lack of knowledge, and technical complexities hinder robotics adoption. - Fear of job displacement further deters adoption. - Financial incentives, training programs, and regulatory support are essential. - Overcoming infrastructure limitations (e.g., power and connectivity) is crucial. - Legal and technical standards need to be clarified.

7.2.1 Streamlining Research and Development Funding for Robotics in the UK

The future is undeniably robotic (Sawyer et al., 2023), poised to play a pivotal role in securing competitive advantages for industrialized nations across the manufacturing and construction sectors. Currently, efforts to transition towards greener, decarbonized construction practices are driving increased funding towards initiatives aimed at reducing environmental footprints in construction projects. However, beyond these initiatives lies the imperative of establishing a robust funding pipeline dedicated to research and development in the UK.

In comparison to other OECD countries and the broader European landscape, the UK lags in embracing robotics. This lag, compounded by its aging population, presents a formidable challenge in terms of investing sufficiently in the development of next-generation robotics that prioritize sustainability while enhancing health and safety standards in the construction industry. Data from the Health and Safety Executive (HSE) underscores the urgency for increased investment in research and development, as evidenced by the persistent number of injuries and fatalities resulting from traditional construction activities (HSE, 2023). These figures surpass those observed in other sectors within the UK. While the inevitability of injury risk is acknowledged, the argument stands that the incidence can be significantly minimized through the adoption of robotics, offering a viable solution to stem the steady stream of reported casualties.

To accelerate research and development (R&D) in robotics and ensure its practical applicability, the UK must strategize on fostering industry-relevant research. This entails initiatives such as robotics showcases, the promotion of robotics boot camps in educational institutions, and increased support for universities engaging in robotics R&D, building on existing efforts at institutions like the University of Lancaster and the University of Loughborough. Seed funding should be allocated to bolster robotic innovation and development, especially within the construction sector. A robust investment pipeline is essential, drawing contributions from both governmental sources and construction stakeholders. Government and stakeholder funding catalyzes stimulating innovative ideas and initiatives, particularly supporting small businesses at the local and national levels to drive forward the advancement of robotics technologies.

In addition to funding, investing in MSc and PhD research focused on construction robotics is crucial. Such research holds promise as a solution to persistent health and safety challenges in the UK construction industry. Increased investment from construction stakeholders will further fuel the pipeline of robotic development, aligning it with industry requirements. Encouraging bids for robotic research aimed at directly addressing ongoing construction-related injuries or fatalities serves as a proactive approach. By doing so, stakeholders in the construction sector contribute significantly to transforming problems into innovative solutions.

Moreover, as artificial intelligence, machine learning, and big data increasingly shape the digital landscape and interactions of machines, research and development become indispensable. However, the UK's focused efforts in research and development offer tailored solutions to specific challenges, with due consideration for environmental impact. This approach enhances the potential for catalyzing robotic adoption, bridging the gap between industry demands and the theoretical necessity for robotics.

7.2.2 Encouraging domestic production of robots.

The geopolitical perspectives explored in this thesis underscore the importance of localizing robot production for national interests and industrial significance, as exemplified by the success stories of Japan and South Korea. Currently, domestic robot production in the UK remains low, despite government funding directed towards robotics development primarily in fast-growing sectors such as manufacturing, nuclear, and transportation. However, given the planned investments in construction in the UK, it is crucial to expand localized robot production to encompass the needs of the construction industry.

Incentivizing local production requires more than just initial funding; it also necessitates government intervention through measures such as tax rebates and holidays for companies in the construction sector or organizations producing robotics. The significance of this lies in the recognition that while there is still a preference for conventional construction approaches in the UK, the future demands efforts to digitize and automate traditional processes, akin to the rapid infrastructure construction witnessed in China. A key factor contributing to China's construction acceleration is its adoption of technology, much of which stems from localized innovations. Boosting local production of robotics transcends mere aspiration; it demands concerted efforts from both key stakeholders and the government. This entails prioritizing robotic development as a pathway to catalyze growth and enhance efficiency in the global technological race. To achieve this, government bodies and research institutions must invest in more robotics laboratories to facilitate the simulation of robotic use and foster their development.

While the UK no longer mines iron ore deposits as it did during the Industrial Revolution due to environmental concerns, an alternative approach to obtaining cleaner iron ore for robotic development involves re-melting steel scrap. This consideration is crucial given that raw materials are a vital component of local production. In the absence of feasible alternatives, the UK has the opportunity to reconsider its approach to robotics and promote its utilization at the micro-level, enabling small industries to experiment with and implement this technology before scaling up to larger applications.

7.2.3 Saliency of Roadmap for Robotic Adoption

A tailored roadmap for the adoption of construction robotics in the UK is both imperative and pivotal for achieving significant progress in robotic uptake. The government's establishment of a comprehensive 5-year or longer roadmap will provide a guiding framework supported by policy measures outlining how robotics in the UK, particularly in the construction sector, will be implemented. The overarching aim of a robotic roadmap is to delineate a strategic plan that articulates the overarching objectives for developing and adopting new technology, thereby paving the way for a technologically advanced future, along with the requisite investment pipeline to realize these objectives. Currently, the UK lacks a roadmap for technological adoption in the construction sector, signifying a gap that warrants attention. This gap underscores two key points: firstly, while construction injuries constitute a significant health and safety concern, the introduction of technology as a solution to address future occurrences has not been deemed a priority. Secondly, construction stakeholders have yet to perceive this as a substantial risk necessitating intervention, as evidenced by this study.

Developing and implementing a roadmap for robotic adoption in the UK, particularly within the construction sector, serves as a foundational framework for evaluating the current state of robotic adoption. It delves into essential aspects such as identifying needs, priorities, challenges, and necessary changes. Moreover, it extends beyond mere assessment to explore viable solutions for addressing talent gaps, devising effective intervention strategies, and providing a comprehensive framework for navigating the path toward global competitiveness and innovation in the construction industry. Central to this roadmap is the establishment of clear and measurable objectives, ensuring they are achievable, trackable, and attributable to performance evaluation, as emphasized by Kirlay et al. (2020). Furthermore, it entails considerations regarding how the roadmap aligns with commercial and industrial requirements while simultaneously minimizing environmental footprints. In addition to this, there is a pressing need to develop a roadmap for the integration of artificial intelligence and emerging digital technologies within the construction industry. This roadmap should particularly focus on aspects such as data utilization, privacy, and data protection. It must address how the construction sector can adapt to the significant changes brought about by digital innovations, ensuring that the integration process aligns with future needs and requirements.

7.2.4 Upskilling Programmes to Address Skill Shortages

A major insight from the interviews highlights a significant skill shortage in the UK construction sector, which is crucial for advancing robotic development and innovation. This issue is exacerbated by the UK's aging population and a limited pipeline of talent in STEM and robotics, essential for industry progress. Addressing this skill shortage requires concerted efforts from both the UK government and the construction industry to make careers in robotics more attractive. By offering opportunities and incentives, the sector can attract the necessary talent with the technical skills and expertise needed to handle, operate, and maintain robotics at the highest level of functionality. At the industry level, any indigenous development must align investment with the availability of a skilled talent pipeline. This alignment is essential to prevent labor shortages and reduce reliance on expatriates for robotic development. According to UKVI (2022), the UK is currently experiencing a shortage of engineers, which complicates the design, deployment, and implementation of robotics and automation. This situation underscores the need to develop specialized educational courses tailored to address the skill gap at various levels, including Level 3 to Level 7 apprenticeships and degree programs.

Addressing this issue requires a four-pronged approach, as highlighted by interview insights. First, the UK curriculum needs updating to include innovations and robotic development, ensuring future generations are equipped to meet industry demands. Introducing children to the theory and practical applications of robotics from a young age will better prepare them for careers in the construction industry. This approach is already in place in countries like China, Japan, and South Korea, where children are exposed early to robotics and other innovations, positioning them to better understand and utilize these technologies.

Another effective approach to bridging the talent pipeline is work-integrated learning. This pathway aligns industry knowledge with classroom learning, positioning students to understand real-life applications of their education and better preparing them for industry needs upon graduation. Work placements serve as a vital link between theory and practice, allowing students to develop and hone skills that meet industry standards. These placements also enhance existing systems by learning from industry experts. Additionally, work-integrated learning facilitates practical knowledge and skills transfer through mentorship, significantly improving technical competencies.

Significant progress in the use of robotics in construction projects has been made by countries outside the UK, presenting opportunities for knowledge transfer that can be adapted to the UK context. Despite the complexities of legal, political, and economic considerations, collaboration between similar jurisdictions has proven effective in enhancing the quality of information, data, and skills transferable across industries. This exchange of best practices can lead to comprehensive applications in technology. Adopting technology transfer allows the UK construction industry to learn from other sectors, using these insights as a foundation to gauge and modify similar innovations, ensuring they achieve the desired outcomes. This approach not only accelerates the adoption of advanced technologies but also ensures that the industry benefits from the proven successes of others.

7.2.5 Addressing Investment Disparities in Robotics

Insights from the interview data reveal a significant disparity in investment in robotics for the construction sector compared to other industries in the UK. This unequal investment indicates that the construction sector receives significantly less funding. Previous discussions highlighted that of the total investment from UK businesses in robotics and autonomous systems, aimed at generating £6.4 billion ($8.41 billion) for the UK economy by 2035, the majority is allocated to the automotive, manufacturing, and health industries. According to the Department for Business, Energy, and Industrial Strategy (BEIS, 2023), less than 1.5% of this total investment is directed towards the construction sector. Given the importance of construction in the UK, this underinvestment not only reflects a lack of government and industry interest but also acts as a disincentive for adopting robotics, as the investment does not match the sector's potential or needs.

According to the British Automation and Robot Association (BARA), the food and beverage industry became the second-largest purchaser of automation, following the automotive sector, for the first time in 2021. For SMEs in the UK manufacturing sector, there has been a substantial increase in investment in robotics innovations, leading to the normalization of robotics in manufacturing processes and resulting in higher production rates. However, the scale of robotics and automation is most effective for large production volumes and higher-value products, making it particularly suitable for the construction industry. Addressing the investment imbalance and increasing the adoption of robotics in construction could significantly enhance productivity and economic contribution, aligning with advancements seen in other sectors.

While the case for increasing investment in robotics in the UK is compelling, it is crucial to align this investment with industry appetite and the willingness of stakeholders and consumers in the construction sector. This necessitates a paradigm shift from conventional construction processes to automation. Although concerns about job loss, unemployment, and other macroeconomic issues are valid, the long-term benefits of transforming automation and construction in the UK make this shift essential. Moreover, there is no consensus in the literature that innovation leads to significant job loss. Instead, it often results in more efficient ways for humans to perform tasks (Mikas et al., 2020). Embracing robotics in the construction industry could enhance productivity, improve quality, and drive economic growth, underscoring the importance of adopting new technologies despite initial concerns.

The responsibility for investing in robotics to incentivize its use does not solely fall on the industry; universities also play a crucial role in ensuring that the adoption of these technologies aligns with research and laboratory efforts. This underscores the importance of research institutes and universities in funding investments for research and innovation to facilitate robotics and innovation interventions. For example, UK Research and Innovation should establish a dedicated funding stream for robotics and automation in the construction sector to address critical skills gaps and stimulate interest in innovation and robotics development. Additionally, research councils such as Innovate UK and Research England should revamp their funding structures and collaborations to prioritize robotics and automation in the construction sector. This focus is particularly vital for the construction industry to enhance worker safety and improve overall productivity.

The Industrial Strategy Challenge Fund, initiated by the UK government in 2017 to bolster research and innovation and elevate the UK as a global leader, must adopt a comprehensive approach to include the underrepresented construction sector in its funding pipeline. The focus areas of this fund, along with supportive initiatives strengthening collaborative projects between businesses, academia, and other stakeholders, need to be expanded to encompass all aspects of the UK's industrial needs. This includes aspects involving construction, which is expected to significantly contribute to GDP, particularly amidst the shift towards cleaner and greener building and infrastructure design and construction.

The EU Horizon 2020 collaboration offers another avenue for advancing cutting-edge collaboration between research and industry across Europe, fostering the development of robotics for construction projects in the UK. Despite Brexit, the UK's association with Horizon Europe, the successor program to Horizon 2020, continues to drive groundbreaking research in robotics, fostering economic growth and societal development (EU Fund, 2022). This collaboration presents a crucial pathway for knowledge transfer, benefiting the discourse on robotics' role in improving construction safety standards in the UK.

While the UK has witnessed the establishment of new laboratories like the National Robotarium at Heriot-Watt University in collaboration with Edinburgh University, aimed at advancing robotic research and innovation and fostering commercialization efforts, progress in commercializing industrial robotics for construction has been sluggish. Collaborative efforts, such as those with the Bristol Robotics Laboratory in conjunction with the University of Bristol and the University of the West of England, have primarily focused on manufacturing, neglecting the construction sector's potential.

This oversight risks leaving the construction industry underserved and underutilized in terms of opportunities for robotics development and advancement. This sentiment is echoed in the International Federation of Robotics (IFR) report on investment trends. Investment in robotics saw a five-year low in 2023, particularly affecting autonomous vehicles. However, the largest sector for investment was in vertical-specific robots, primarily in defense and logistics. While investment in LiDAR, sensors, chips, and motors has seen growth, there remains a significant gap in investment and research focus for robotics in the construction sector. Closing this gap is crucial to fully leverage the potential of robotics to transform construction processes and outcomes.

7.2.6 Addressing Upfront Costs: Policy Incentives

The survey data highlights upfront costs as a major disincentive for the adoption of robotics compared to traditional construction methods. While the long-term benefits of robotics outweigh initial procurement costs, many small construction businesses in the UK struggle to afford the installation, adoption, and use of robotics in construction safety practices. Moreover, the upfront costs pose a risk of inflating the total cost of construction procurement, which may not be welcomed by consumers.

The disparity in affordability skews the adoption of robotics in construction. While larger construction companies may have the resources to invest in robotics to enhance safety initiatives and health & safety policies for their workers, smaller companies may struggle to accommodate these costs within their budgets. This raises questions about the universality of adoption in terms of availability, accessibility, and equity. To address this challenge, policy incentives are essential. Implementing measures to reduce upfront costs, such as subsidies, tax incentives, or grants, can make robotics more accessible to small construction businesses. By mitigating financial barriers, these incentives can promote widespread adoption of robotics in construction, ensuring that safety initiatives and technological advancements are accessible to all stakeholders, regardless of their size or financial resources.

Availability pertains to the extent to which all stakeholders can procure a particular construction robot or integrate it into their team for human-robot collaboration. It is also contingent on mass production, where a competitive market drives down prices, making robots commercially available and purchasable. Accessibility encompasses both local and external factors. Locally, it involves ensuring that robots are readily accessible when needed, reliant on local manufacturing capacity, and the availability of raw materials without disrupting the supply chain. Externally, it involves companies being able to procure robotics without encountering legal, technical, or regulatory bottlenecks that impede procurement.

Accessibility is demand-driven, influenced by price and local availability. If robotic technology is not accessible, it affects price modulation and hinders its utilization due to import duties and compliance checks. Equity refers to ensuring equitable access to technology at a commercial level, free from technical and economic barriers that limit access and availability. This ensures that all stakeholders have fair opportunities to leverage robotics for their needs (Lambart et al., 2022). Enhancing availability, accessibility, and equity in robotics adoption involves addressing barriers to procurement, streamlining regulatory processes, and fostering a competitive market environment that promotes innovation and affordability. This approach ensures that robotics technology is accessible to all stakeholders, regardless of their size or resources, fostering widespread adoption and maximizing the benefits of human-robot collaboration in construction.

The UK government holds significant influence in equalizing the competitive landscape for robotic innovation through policy interventions. Government incentives can level the playing field, providing SME companies with equitable access to opportunities for digitization and automation. While efforts are underway, there's room to scale up initiatives, particularly in advancing automation utility and ensuring industry readiness for robotics through favorable policy measures.

These policies could encompass favourable immigration regulations, facilitating skilled migrants' entry to the UK and creating tech pathways to expedite the importation of experienced automation experts. Additionally, reskilling and upskilling policies are imperative to counteract the age and skill decline in the UK workforce, crucial for enhancing productivity. As Reeves (2021) notes, the switch to automation poses challenges for businesses and workers, with concerns over livelihoods and job disruption. Thus, while government policies provide direction for robotic technology adoption, the gap between policy, plans, and implementation remains unresolved. Addressing this disconnect against the backdrop of economic impacts is essential to expedite the uptake of robotics technologies in the UK.

7.2.7 Enhancing Health and Safety in the Construction Industry through Collaboration

The health and safety sector in the UK highlights the need for greater collaboration between industry stakeholders in the construction sector and regulatory agencies responsible for preventing and reporting construction-related injuries and fatalities. This collaboration is crucial to designing robotics that effectively prevents further injuries and fatalities in construction while ensuring that specifications align with robotic requirements for design and use. Moreover, developing standards for the use of robotics in construction emerged as a key finding from interview insights. This is particularly important as robotics in construction may pose additional risks to health and safety.

Addressing these risks requires the introduction of moderating health and safety rules specific to robotic use. However, the lack of standards development, certification, and established protective methods, similar to personal protective equipment (PPEs), creates significant roadblocks to robotic adoption in construction. Without these standards, the idea of universal application in the UK industry may be hindered. Therefore, developing industry standards for the use of robotics in construction is essential to ensure the health and safety of workers. This standardization will provide clear guidelines on how robotics should be used in construction, mitigating risks and promoting a safer working environment for all.

7.2.8 Raising Public Awareness: Shifting Perceptions of Robotics in the UK

Improving public perception regarding robotics in the UK emerged as a significant theme from respondent insights. Currently, perceptions within the construction sphere often revolve around fears of job displacement, increased unemployment, and threats to livelihoods and skill development opportunities. It's essential to broaden awareness within the digital innovation space, highlighting how AI and machine learning innovations can positively impact the construction industry. Enhancing awareness involves organizing robotic and automation awareness workshops for the public, aiming to educate them about the utility, range, benefits, and possibilities robotics brings to construction. This includes their role in preventing injuries and supporting workforce health and well-being. By incentivizing technology acceptance, these efforts contribute to normalizing robotics in the workplace and fostering integration, particularly in human-robot collaboration. Furthermore, providing upskilling opportunities for construction staff enhances their knowledge and understanding of new technologies, empowering them to adapt to and effectively utilize these advancements in the construction setting. This proactive approach not only addresses concerns but also promotes a positive outlook on robotics, paving the way for their effective implementation and integration in the construction industry.

The duration and technical complexity required to learn and adapt to new technology significantly influence perceptions of its use and ultimately impact motivation for adoption. This underscores the usability challenges associated with new technologies and their crucial role in determining industry uptake. Consideration should also be given to the adjustment period and opportunities for feedback to enhance construction work processes. This approach not only fosters a stronger connection between construction workers and technology but also allows for the gradual introduction of robotics and automation, easing concerns and building trust among stakeholders. As revealed in this study, gradual integration instills greater confidence in robotic technology compared to sudden shifts. Moreover, emphasizing sustainability and the transformative potential of robotics and automation is essential for driving customer engagement and acceptance.

Beyond the added costs, consumers need to be informed about the advantages of utilizing robotics in construction, including reduced project completion times and assurance of maintained project quality. This aligns with the concept of scalability, which in construction robotics entails expanding usage to meet demand, enabling both small and large stakeholders to access these technologies for everyday operations. Unlike in manufacturing and services, where robots are often customized for specific environments, construction robots are typically capital-intensive and require multiple units for diverse tasks, posing scalability challenges.

A recent PwC report highlights that many small stakeholders perceive advanced robotics in construction as difficult to attain, reinforcing the perception that robotics is primarily accessible to larger companies (PwC, 2023). By emphasizing the scalability and benefits of construction robotics, stakeholders can overcome these barriers, demonstrating how robotics can streamline processes and enhance project outcomes across the board. This proactive communication is essential for promoting wider adoption and ensuring that the benefits of robotics are accessible to all stakeholders in the construction industry.

7.2.9 Address Core Barriers to Robotic Adoption

The adoption of robotics in the UK construction industry faces significant barriers stemming from economic and legal factors. These hurdles include the high costs associated with purchasing and implementing robots, particularly challenging for small and medium-sized businesses. Additionally, a notable lack of knowledge and skills in effectively operating robots hinders adoption, alongside the complexity of installation, programming, and integration processes, which can be time-consuming and daunting.

Moreover, the limited flexibility of many robots, designed for specific tasks, poses challenges in adapting them to varied environments. Fear of job loss further compounds these barriers, as concerns about potential displacement deter companies from embracing robotic technology. Addressing these obstacles demands multifaceted strategies, such as providing financial incentives, offering comprehensive training programs, streamlining installation processes, and fostering a supportive regulatory framework. By proactively tackling these challenges, the construction industry can unlock the transformative potential of robotics, enhancing innovation and efficiency throughout the sector.

Legal and regulatory barriers pose significant challenges, as the absence of clear regulations and standards for robot usage complicates adoption efforts. Moreover, technical limitations persist, with robotics technology facing hurdles in sensor capabilities, perception, mobility, and adaptability, limiting their applicability in certain sectors. Concerns regarding data privacy and security arise due to robots' potential collection and transmission of sensitive data. This uncertainty is exacerbated by companies' hesitancy regarding the return on investment from robot implementation, hindering justification for initial investment.

Additionally, organizational resistance within companies, particularly in the construction sector, presents a formidable obstacle. Despite the potential benefits, reluctance to embrace new technologies like robots persists. Furthermore, inadequate infrastructure on construction sites, including insufficient power supply and internet connectivity, poses practical challenges to robot deployment, further impeding adoption efforts. Addressing these multifaceted barriers demands comprehensive strategies and collaborative efforts to foster a conducive environment for robotics integration across industries.

7.3 Towards a Roadmap for Robotic Adoption in the UK Construction Industry

The preceding analysis underscores the importance of developing robotics to meet industry specifications and evolving needs, particularly as the challenges within the UK construction industry are continuously changing. Robotics innovation plays a crucial role in driving the advancements necessary to propel the industry forward, given the myriad possibilities enabled by its use. In recent years, robotic technologies have significantly transformed the construction industry ecosystem, altering traditional workflows. Moreover, emerging innovations such as the Internet of Things (IoT), machine learning, and artificial intelligence have further expanded the transformative potential of robotics, transforming the industry even further.

This thesis explored the feasibility and potential of robotic technology in mitigating construction-related injuries in the UK. It assessed the role of robotics within the context of various innovations aimed at preventing such injuries. A key part of the analysis focused on theoretical frameworks, particularly the diffusion of innovation theory. This theory posits that the adoption of new technology progresses from early adopters to widespread integration into everyday practices, eventually facing resistance from laggards reluctant to embrace technological change. Findings from interviews and surveys revealed that while construction stakeholders have shown strong interest in adopting robotics, especially for reducing repetitive injuries, substantial momentum is still required to achieve mainstream adoption. This is influenced by numerous factors, including navigating complex regulatory environments, addressing scalability issues, upfront costs, employment challenges, and the willingness of stakeholders to embrace change and innovation.

Meaningful efforts towards advancing robotic construction in the UK must critically consider and balance the variables implicated in economic, financial, industry, and broader technological challenges. Additionally, it is crucial to anticipate how the industry can respond, what support is needed, the enabling environment that must be established, and the current architecture of the construction industry that limits the advancement and use of robotics. Government policies play a pivotal role and must be activated to facilitate any acceleration in the adoption of robotics. Furthermore, efforts must recognize the impact of perception within the industry and the underlying motivations for adopting robotics. Research should focus on sustainable and resilient dimensions for the future of robotics in the UK, ensuring a comprehensive and forward-thinking approach.

7.3.1 Take-off considerations for robotic adoption roadmap in the UK

The essence of road mapping lies in establishing a strategic process that outlines actionable steps needed to achieve predetermined goals or, more precisely, to translate conceptual ideas into a tangible reality. Thus far, the research discussions have underscored the importance of moving beyond merely articulating the challenges or reasons behind the sluggish uptake of robotics in the UK construction industry. However, there remains a scarcity of studies that progress from merely identifying issues to crafting a roadmap for realizing solutions. The fundamental objective of the roadmap is to serve as a starting point for construction stakeholders to implement the insights gleaned from this research and reconsider how robotic adoption can be achieved, whether at a small or large scale, amidst the challenges inherent in this activity. To facilitate this discourse, a series of considerations is proposed, beginning with the take-off stage, which addresses the core issues requiring attention to propel efforts forward into the subsequent phases.

The take-off phase marks a critical juncture where robotics transitions from novelty to standard practice, becoming deeply ingrained, socially accepted, and institutionalized within the construction industry. During this phase, a substantial portion of the challenges associated with adoption have been mitigated, and robotic implementation has reached its zenith. In the final phase, known as the full integration phase, the roadmap delineates the delicate equilibrium achieved with robotics. This phase signifies the complete assimilation of robots into the industry, where the construction sector has adeptly adapted to ongoing evolution, change, and now plays a pivotal role in shaping the trajectory of technology. While the notion of reaching a final phase may seem idealistic, especially considering the perpetual need for adaptation and innovation inherent in robotics, this phase signifies not only the future possibilities enabled by robotics but also how these intersect with various key variables that drive their evolution.

The notion of take-off considerations refers to the critical issues identified in this thesis that must be addressed before roadmapping efforts can be fully realized. It's noteworthy that some of these issues cannot be resolved with a quick fix but require concerted and intentional efforts tailored to tackle the underlying problems and propel the development of robotics in the construction industry. Additionally, it's crucial to recognize that the issues discussed below do not encompass all the challenges facing the construction industry in the UK. However, they represent key issues that must be addressed to initiate significant strides toward automating the construction sector in the UK.

7.3.2 The Resilience Factor

At the heart of developing robotics tailored to meet the needs of the construction sector lies the crucial aspect of resilience. This resilience entails the capacity of robots to withstand the complexities, hazards, and challenging environments inherent in the construction industry. Therefore, one of the primary considerations in developing robots is their resilience, which directly addresses the industry's requirements for productivity, safety, and efficiency.

Resilience, defined as the ability of a robot to effectively fulfill its intended design purpose without errors resulting from various factors such as technical failures, parallax, or susceptibility to human error during core functions execution, is paramount (Shu et al., 2022). This concept is closely intertwined with adaptability, which denotes a robot's capability to carry out its core functions without encountering breakdowns or escalating health and safety risks (Reed et al., 2022). While industry design efforts aim to adhere to these fundamental principles, the degree to which robots demonstrate such capabilities in real-world performance within construction settings remains a central concern. This discussion also intersects with the notions of reliability and perception. Reliability, in this context, serves as a critical determinant of whether humans can trust that robots will consistently function at the expected level without unexpected disruptions or failures. Therefore, ensuring that robotics in construction embodies resilience, adaptability, and reliability is essential for fostering trust and confidence in its effectiveness and safety within the industry.

Any roadmap devised for the industry must meticulously address how robotics is engineered for longevity, ensuring it endures and maintains peak performance across diverse landscapes and situations within the construction sector. Resilience also encompasses their ability to withstand and mitigate privacy and data security concerns inherent in their connection with computers and AI systems at large. They must remain impervious to data security vulnerabilities, safeguarding the integrity of construction data.

Furthermore, ecological considerations are paramount. Robotics must be designed to be environmentally friendly, aligning with net-zero emissions goals by minimizing fossil fuel usage and carbon footprint. Material sourcing becomes crucial here, with a need to determine what percentage should be domestically sourced in the UK and how imported robotics can be suitably adapted for the UK environment. Additionally, attention must be given to the design, integration, adoption, and functionality of these systems to cater to the evolving needs of the construction industry. Moreover, there's a burgeoning consideration regarding the collaboration between robots and humans on construction sites, with careful thought required on how these robots can effectively complement human workers and vice versa. While it may not be the foremost concern in the roadmap's progression, integrating technology considerations forms the core of its evolution. Any significant efforts towards achieving progressive robotic integration in construction must incorporate these considerations into the central product—the robot itself.

7.3.3 Building synergy with industry/Consultation

Before initiating any roadmap, consulting with relevant stakeholders in the construction industry is vital. The research underscores a divergence of opinions regarding the current use of robots in the UK construction sector. These concerns revolve around the balance between productivity gains and the potential economic impact on employment. One significant barrier to the adoption of robotic technologies in the UK is the upfront cost implications. Construction stakeholders carefully weigh cost-benefit considerations and return-on-investment before committing to implementing these technologies on construction sites. Economic factors such as market demand, client perceptions, and the financial impact of robotization on building costs and site design play crucial roles in decisions regarding the adoption of robotic technology in construction projects.

The cost-benefit analysis of adopting robotic technology involves weighing financial gains against several factors, including injuries prevented, implementation costs, and the availability of technical expertise to operate these systems, all in consideration of the expected return on investment (ROI). These uncertainties underscore a fundamental absence of a roadmap for integrating robotics into the construction industry. The lack of a strategic plan to define and implement the rollout of robotics and its transformative potential in the UK construction sector emphasizes the necessity for industry consultations. Industry consultations should encompass stakeholders ranging from contractors, engineers, site managers, health and safety managers, construction workers, to trade unions and lobbying groups. This inclusive approach allows stakeholders to aggregate and provide feedback, addressing concerns, prospects, and challenges organizations face in adopting robotics. Such consultations are crucial for developing a comprehensive roadmap that navigates the complexities of integrating robotics into the construction industry effectively.

The UK is emerging as a key player in the global race to adopt robotics in construction, leveraging its strengths in innovation, engineering, and research and development (Segay et al, 2021). British companies and research institutions are pioneering advancements in robotic construction technologies, including robotic bricklaying, autonomous drones for site monitoring, and robotic exoskeletons for worker assistance. Despite these advancements, the UK faces stiff competition from other countries, particularly China, the United States, and Germany, which have made significant investments in robotic construction technologies (Finbarr et al, 2022).

The UK's transition to robotic adoption in construction presents both challenges and opportunities. While robotic technologies have the potential to revolutionize the construction industry, their widespread deployment may exacerbate existing disparities in employment and income distribution, leading to social and economic tensions. However, the adoption of robotics also presents opportunities for the UK to enhance its global competitiveness, drive innovation, and create new job opportunities in high-tech industries.

As the UK formulates its strategies for robotic adoption in construction, it must consider geopolitical factors, including technological dependence, intellectual property rights, and strategic partnerships. Collaborative initiatives with like-minded allies and international organizations can help mitigate risks associated with technological dependence and safeguard national interests. Moreover, the UK should prioritize the development of indigenous robotic technologies and capabilities to maintain technological sovereignty and reduce reliance on foreign suppliers. This requires sustained investment in research and development, as well as strategic partnerships with industry and academia.

The geopolitics of robotic adoption in construction are reshaping the global construction landscape, with implications for economic competitiveness, technological innovation, and national security. As the UK races to adopt robotic technologies, it must navigate geopolitical complexities, capitalize on its strengths, and address challenges to maintain its position as a global leader in construction innovation. By leveraging strategic partnerships, investing in research and development, and fostering a skilled workforce, the UK can unlock the full potential of robotics in construction and secure its place in the future of the global construction industry.

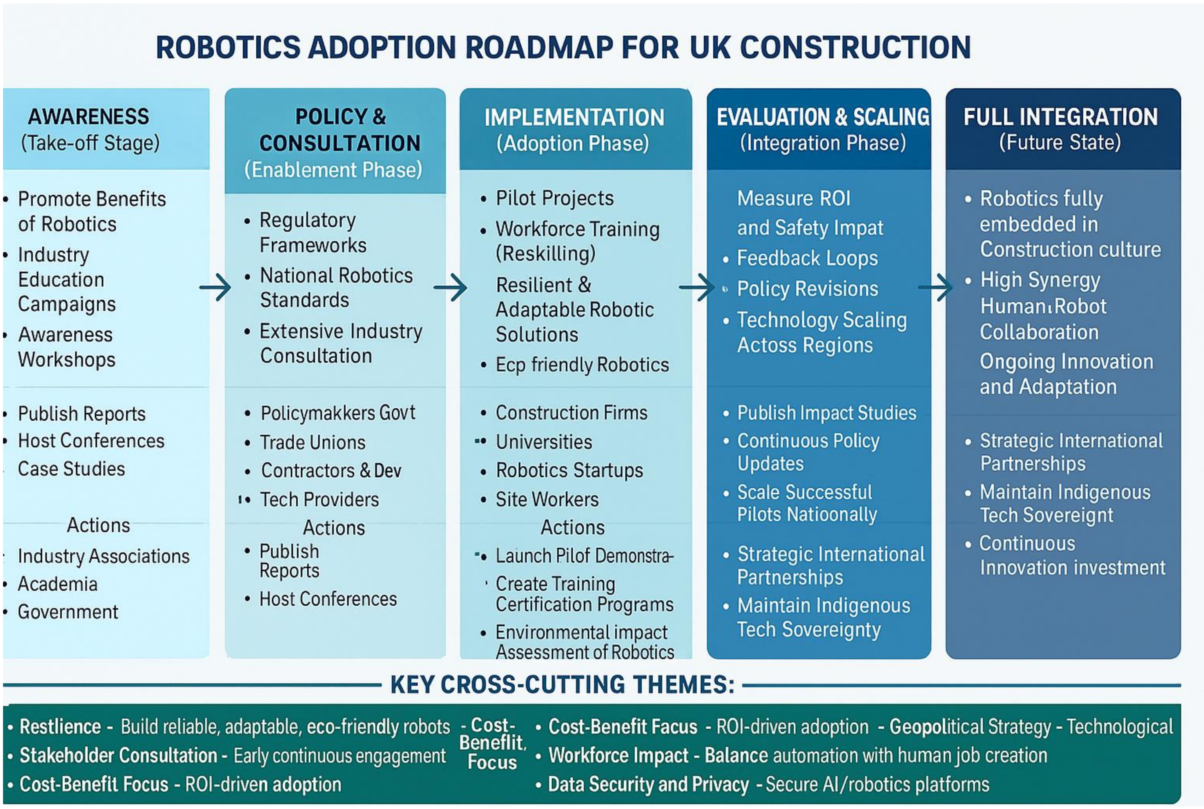

Figure 30: Robotics Adoption Roadmap for UK Construction

7.4 Limitations of the Research

The study has critically explored evidence to synthesize results that provide insights into the prospects and barriers to robotic adoption for preventing construction injuries in the UK. While the study employed an appropriate methodology that aligns with the research inquiry's scope, several limitations must be acknowledged. Firstly, inherent limitations exist in the interpretive nature of interviews, which can introduce bias from respondents. Despite best efforts to mitigate this and prevent confounding bias, these limitations remain a concern. Secondly, due to the impracticality of including every stakeholder in the construction industry, a sampling procedure was necessary. After several months and multiple follow-up emails, only 54 respondents consented, volunteered, and completed the survey form. This limited sample size may affect the generalizability of the findings. Nonetheless, the researcher has taken significant steps to ensure the data's reliability and validity within these constraints.

While the total number of respondents did not represent the entirety of the UK construction sector, they do provide a valuable sample for analysing expert opinions within the industry. Similarly, despite extensive follow-up efforts via LinkedIn, direct emails, and cold outreach over several months, only 10 interviews were conducted. Although this number is not large, the quality of the interviewees offered substantial insights, compensating for the smaller sample size. It is acknowledged that this sample size may not fully capture the diverse perspectives of all construction stakeholders in the UK. Consequently, there may be contrasting opinions or feedback that were not included due to the limited number of participants involved in the analysis and triangulation of the data. Nonetheless, the responses gathered offer a meaningful snapshot of industry sentiments regarding the adoption of robotics for preventing construction injuries.

While this thesis examines health and safety in the UK construction industry, it is noteworthy that it did not cover all emerging and re-emerging health issues that could be addressed by robotic intervention. Additionally, although various types of robotics were assessed, the study focused specifically on those relevant to reducing construction-related injuries. It acknowledges that other types of robotics exist, but the primary interest was in technologies directly impacting injury prevention.

Another constraint faced by this thesis was the impossibility of obtaining feedback from every construction sector across the UK due to the research's scope and logistical challenges. Despite the best efforts, a more generalized response from a wider pool of respondents would have provided a broader perspective on robotic adoption and its challenges. This is particularly important given that infrastructural development is unevenly spread across the UK, and understanding how construction companies operate in different regions, with or without robotics, would offer insights to enrich the research recommendations.

Additionally, the researcher acknowledges the limitation of not employing all available data collection methods. While the chosen methodology was deemed the most suitable for this study, incorporating other research methods, such as unobtrusive observation or participatory research, could potentially uncover new insights. However, these methods were impractical and challenging to implement within the study's constraints.

7.5 Implications for future research

While this study delved into a critical topic amidst the evolving innovations in the construction domain, future research efforts can leverage its findings to advance knowledge in this area. While this study concentrated on the UK context, there is potential for future studies to undertake a comparative analysis, juxtaposing robotic adoption in the UK with analogous jurisdictions in Europe. This comparative approach could illuminate how these regions are adapting to and implementing robotic technologies, shedding light on the challenges impeding their robust integration. Such insights could enrich strategic roadmap planning for robotics in the UK, facilitating accelerated research and innovation based on global best practices. Furthermore, the scope of analysis could extend to a trilateral examination, encompassing comparisons between the UK, Europe, and Asia. Given the significant strides made by Asian countries in the robotization of their construction sector, exploring these cross-jurisdictional comparisons could provide valuable insights into the trade-offs and benefits inherent in the UK's experience.

Future studies can delve deeper into the pivotal role of government policies and investment in dismantling barriers and facilitating the entry point for robotic innovation in the UK. This entails a comprehensive examination of evolving and innovative policies designed to bolster the commercialization of robotics in the UK and alleviate constraints hindering its utilization in the construction industry. Further research should explore how these policies intersect with educational policies and curriculum development aimed at upskilling and reskilling construction workers in the UK. Additionally, it is imperative to investigate regulatory standards and the digital infrastructure necessary to support the accelerated adoption of robotics in the UK. The research should prioritize a policy implication facet, ensuring that its findings carry substantial weight in influencing government policy and shaping the actions of construction stakeholders to demand improvements for enhanced outcomes.

Further research could undertake longitudinal studies to examine how robotic systems are evolving alongside digital systems and how this intersects with the ever-changing needs of the construction industry in the UK. A longitudinal study would provide a deeper understanding of how challenges are evolving and how robotic systems can best address them, given these changes. This should also include an assessment of the UK's progression through the different phases of robotic adoption identified in this thesis.

Future studies can explore how robotics plays a different role not only in injury prevention but also in intelligent injury mitigation within the construction industry. As robotics and robotic systems become increasingly integrated into today's world and extend their influence into the construction sector, understanding their various roles can better position the UK and organizations like the HSE for strategic planning and formulation. Additionally, future research could delve into how road mapping robotic interventions and the different strategies adopted for robotic innovation in the UK can shape the future of robotics in the construction industry. This area of research is continuously evolving, and substantial research efforts are necessary to assess how construction activities are progressing despite the sector's challenges.

Future research should build upon the recommendations to catalyse policy efforts aimed at robotizing and automating the construction sector in the UK. This is crucial considering the rapid acceleration of robotics and digital technology, which will define the trajectory of robotic advancements. While the immediate implications for the UK construction industry may not be fully understood, experiences from other countries highlight the pivotal role robotics will play. Therefore, further research will help mitigate the risk of the UK falling behind, leveraging its existing resources and research and development capabilities to explore how these recommendations can be effectively translated into theory and practice, including influencing the adoption of robotic systems.

Further directions for future research

Several studies analysed in this thesis explored the potential of robotics in construction, but there remains a significant gap in research specifically focused on the UK construction industry and the factors that influence the scalability of these innovations (Wu et al., 2020). As a result, further investigation is urgently needed to assess the feasibility and barriers to adopting new technologies within the UK construction sector. While some studies have approached this issue (Greene et al., 2015; Owolabi et al., 2019; Mariam et al., 2019; Osimhen et al., 2020; Gleed, 2021), their findings lack sufficient evidence to draw definitive conclusions. This thesis has contributed to a yawning gap in the literature and has highlighted the saliency of embedding resilience in the policy-making ecosystem that provides the ambit for construction robotics adoption. It explored the broader factors affecting technology uptake in the UK, particularly from the perspective of key industry stakeholders. However, one undertaking for further research, especially as new technologies emerge is to explore the policy configurations of the construction industry given innovation and transformative changes in other comparable jurisdictions and how this impacts the uptake, feasibility and applicability of robotics in the UK construction domain of the future, especially in response to its regulatory policies on AI and innovation at large.

The United Kingdom has made notable progress in the field of robotics, achieving considerable advancements, yet as this study highlights, it still lags behind many other nations and comparable jurisdictions (Gleeds, 2023). While the UK has grand ambitions for transforming its robotics sector, particularly in manufacturing and services, and improving innovation through research and development funding (UK GOV, 2023), there remains a significant gap between these ambitions and actual implementation. The government's commitment to this transformation is evident in the UK Industrial Strategy, but much more needs to be done to bridge the gap between intention and action if the goal of catching up and advancing is to be realized.

The UK is recognized globally as a leader in robotics, and over the past decade, numerous innovative companies and collaborative research centers have emerged, creating a robust robotics ecosystem. However, there remains a noticeable gap between robotics research and its adoption, particularly in the UK construction industry. While the potential for transforming construction practices with robotics is vast, the slow pace of automation adoption and the hesitancy of stakeholders within the industry have raised critical questions. These include how UK construction priorities are being shaped locally and, ultimately, how this will influence the country's position in the international competitive landscape.

A key issue remains the UK's ability to attract skilled workers and talent from overseas to drive innovation and enhance automation levels within its construction sector. This continued need for external expertise highlights the challenge of aligning the intentions of the UK government with the realities of industry adoption, especially in a global context where innovation and competitive advantage depend heavily on the ability to integrate cutting-edge automation technologies.

This skilled workforce would require a careful calibration of immigration protocols and policies to ensure that the UK remains an attractive destination for talented individuals in the fields of robotics, machine learning, AI, and data science. These experts will contribute to advancing design, programming, integration, interoperability, and the seamless functionality of robotics and human collaboration in the workplace.

The future of AI is inevitable, as advancements continue to drive the infusion and integration of AI and robotics into the workforce. The potential to reduce safety incidents, mitigate risks, and minimize fatalities, especially in high-risk environments such as construction sites, has made the adoption of robotics not only a necessity but an inevitable direction for the future of the construction industry. The UK has established advanced robotics research and AI centers that can accelerate the country's ability to compete in the global arena. However, government priorities remain a crucial factor, and they must be clearly defined to ensure these discussions progress effectively and influence the trajectory of the UK's robotics and AI landscape.

Comprehensive policy analysis

One key finding uncovered in this study is the imperative need for a forensic analysis of the UK's robotics ecosystem and the critical importance of developing forward-looking policies to enhance the uptake of robotics in the UK construction industry. While there has been significant interest in the advancement of robotics, most progress has primarily focused on manufacturing, services, and fast-moving sectors where AI and innovative robotics have been used to improve customer service experiences. A comprehensive policy analysis of the UK construction sector involves carefully assessing what is actionable and what isn't, while considering competitive readiness. It also highlights the ongoing tension between adoption and adaptation, a crucial issue that remains an evolving topic.

A review of the UK's innovation strategy, with a forward-looking approach, positions the construction sector at the forefront. Despite positive advancements in technology adoption, there is a momentum shift towards embracing these technologies and introducing advanced development interventions. One of these interventions involves identifying what actions are feasible. Interviews point to actionable steps to address the ever-changing landscape, particularly regarding the cost of acquiring these technologies and the type of government support necessary to incentivize and boost adoption.

This ties into the impact of public-private partnership arrangements, which are crucial for catalysing change and addressing critical challenges within the construction industry. One potential approach is to reverse course by creating more focused and intentional policy calibrations that incorporate the perspectives of construction workers and stakeholders in the policy process. Roundtable discussions on the nature of these policies and the government's plans to implement them with a forward-looking compass are a crucial starting point for improving the outlook for robotics adoption in the construction industry.

Building on this, the salience of competitiveness and readiness emerges as a key policy issue. The findings of this study highlight the current innovation strategy for AI and robotics and its tenuous outlook. The UK holds significant potential to revolutionize its construction sector and match its EU peers in terms of readiness and competitiveness in robotics adoption. However, several underlying issues need to be addressed to create the space necessary for these technologies to thrive. One prominent area is the UK's readiness to raise the bar on research, funding, and the integration of robotics into the construction sector, particularly as the focus shifts more towards manufacturing.

Projections indicate this is critical, especially as an aging workforce is set to retire, necessitating the introduction of more skilled talent to reduce fatalities and injuries within the sector. The policy issue at hand revolves around how the UK’s readiness will evolve over the next decade, particularly in comparison to countries in Asia, which have made significant strides in industrial robotics adoption. One ongoing concern is how the UK can accelerate and introduce more targeted efforts to ensure stakeholders in the construction industry can fully capitalize on these technologies. Furthermore, the government must provide adequate support to speed up adoption, making robotics a standard practice within the sector.

Future studies can delve deeper into the pivotal role of government policies and investment in dismantling barriers and facilitating the entry point for robotic innovation in the UK. This requires a tailored examination of evolving and innovative policies designed to bolster the commercialization of robotics in the UK and alleviate constraints hindering its utilization in the construction industry. Further research should explore how these policies intersect with educational policies and curriculum development aimed at upskilling and reskilling construction workers in the UK. Additionally, it is imperative to investigate regulatory standards and the digital infrastructure necessary to support the accelerated adoption of robotics in the UK. The research should prioritize a policy implication facet, ensuring that its findings carry substantial weight in influencing government policy and shaping the actions of construction stakeholders to demand improvements for enhanced outcomes.

References

Abou, A., Hamzeh, F. and Al, F. (2020), "*Agent-based modeling to optimize workflow of robotic steel and concrete 3D printers*", Automation in Construction, Vol. 110, p. 103040.

Adami, P., Rodrigues, P.B., Woods, P.J., Becerik-Gerber, B., Soibelman, L., Copur-Gencturk, Y. and Lucas, G. (2021), "*Effectiveness of VR-based training on improving construction workers 'knowledge, skills, and safety behavior in robotic teleoperation*", Advanced Engineering Informatics, Vol. 50, p. 101431.

Afsari, K., Gupta, S., Afkhamiaghda, M., & Lu, Z. (2018). Applications of Collaborative Industrial Robots in Building Construction. In *54th ASC Int. Conf. Proc*.

Afsari, K. and Afkhamiaghda, M. (2020), "*Applications of collaborative industrial robots*", Machines. Technologies. Materials, Vol. 14 No. 3, pp. 96-99.

Afsari, K., Gupta, S., Afkhamiaghda, M. and Lu, Z. (2018), "*Applications of collaborative industrial robots in building construction*", 54th ASC Annual International Conference Proceedings, pp. 472-479.

Aghimien, D.O., Aigbavboa, C.O., Oke, A.E. and Thwala, W.D. (2019), "*Mapping out research focus for robotics and automation research in construction-related studies: a bibliometric approach*", Journal of Engineering, Design and Technology, Vol. 18 No. 5, pp. 1063-1079.

Akinradewo, O.I., Aigbavboa, C.O., Okafor, C.C., Oke, A.E. and Thwala, D.W. (2021), "*A review of the impact of construction automation and robotics on project delivery*", IOP Conference Series: Materials Science and Engineering, Vol. 1107 No. 1, p. 12011.

Akshatha, D., Vimala, M.S. and Manjula, M. (2017), "*Robotics in construction technology*", International Journal of Advanced Research in Science and Engineering, Vol. 6, No. 7.

Almeida D, Shmarko K, Lomas E. The ethics of facial recognition technologies, surveillance, and accountability in an age of artificial intelligence: a comparative analysis of US, EU, and UK regulatory frameworks. AI and Ethics. 2021. https://doi.org/10.1007/s43681-021-00077-w.

Anagha, R., & Xavier, A. S. (2020). A review of ergonomic risk factors causing musculoskeletal disorders among construction workers. *Int. J. Eng. Res. Technol*, *9*(06), 1234-1236.

Anna, A., Pacher, M., Li, H., Cote, N., Pastrana, R., Gramazio, F. and Kohler, M. (2021), "*Robotic assembly of timber joints using reinforcement learning*", Automation in Construction, Vol. 125, p. 103569.

Anwer, S., Li, H., Antwi-Afari, M. F., & Wong, A. Y. L. (2021). Associations between physical or psychosocial risk factors and work-related musculoskeletal disorders in construction workers based on literature in the last 20 years: A systematic review. *International Journal of Industrial Ergonomics*, *83*, 103113.

Babalola, A., Musa, S., Akinlolu, M.T. and Haupt, T.C. (2021), "*A bibliometric review of advances in building information modeling (BIM) research*", Journal of Engineering, Design and Technology, doi: 10.1108/JEDT-01-2021-0013.

Bademosi, F. and Issa, R.R.A. (2021), "*Factors influencing adoption and integration of construction robotics and automation technology in the US*", Journal of Construction Engineering Management, Vol. 147.

Beardsley, K. (2015). Introducing the UK Construction (Design and Management) Regulations 2015. In *Proceedings of the Institution of Civil Engineers-Civil Engineering* (Vol. 168, No. 1, pp. 8-8). Thomas Telford Ltd.

Bock, T. (2015). The future of construction automation: Technological disruption and the upcoming ubiquity of robotics. *Automation in Construction*, *59*, 113-121.

Bock, T., & Linner, T. (2016). *Construction Robots: Volume 3: Elementary Technologies and Single-Task Construction Robots*. Cambridge University Press.

Bock, T. (2015), "*The future of construction automation: technological disruption and the upcoming ubiquity of robotics*", Automation in Construction, Vol. 59, pp. 113-121.

Bock, T. (2017), "*Automation and robotics in building construction*", ISARC proceedings of the 15th International Symposium on Automation and Robotics in Construction: Automation and robotics–today's reality in construction, p. 98.

Bogue, R. (2018), "*What are the prospects for robots in the construction industry?*", Industrial Robot: An International Journal, Vol. 45 No. 1, pp. 1-6.

Boon, J., Yap, H., Pei, K., Lee, H. and Wang, C. (2021), "*Safety enablers using emerging technologies in construction projects: empirical study in Malaysia*", Journal of Engineering, Design and Technology, Boulos, T., Sartipi, F., & Khoshaba, K. (2020). Bibliometric analysis on the status quo of robotics in construction. *Journal of Construction Materials*, *1*, 2-3.

Bryan, F. and Mahya, S. (2021), "*Future of construction work at the human-technology frontier*", Collaborative Project Delivery Lab.

Capitani, S.L., Bianchi, M., Secciani, N., Meli, E., Ridolfi, A. and Pagliai, M. (2021), "*Model-based mechanical design of a passive lower-limb exoskeleton for assisting workers in shotcrete projection*", Meccanica, Vol. 56 No. 1, pp. 195-210.

Cardoso, L., Silva, R., de Almeida, G.G.F. and Santos, L.L. (2020), "*A bibliometric model to analyze country research performance: scival topic prominence approach in tourism, leisure and hospitality*", Sustainability, Vol. 12 No. 23, pp. 1-27.

Construction Industry Council (CIC), Report of CIC Manpower Forecasting Model 2018 (Skilled Construction Workers), CIC, Hong Kong, 2019, https://www.cic.hk/files/page/56/Manpower.pdf Accessed date: 1 February 2021.

Darlow, G., Rotimi, J.O.B. and Shahzad, W.M. (2022), "*Automation in United Kingdom's offsite construction (OSC): a status update*", Built Environment Project and Asset Management, Vol. 12 No. 1, pp. 38-52.

Delgado, J.M.D., Oyedele, L., Ajayi, A., Akanbi, L., Akinade, O., Bilal, M. and Owolabi, H. (2019), "*Robotics and automated systems in construction: understanding industry-specific challenges for adoption*", Journal of Building Engineering, Vol. 26, p. 100868, doi: 10.1016/j.jobe.2019.100868.

Department for Digital, Culture, Media & Sport. Digital regulation: Driving growth and unlocking innovation; 2021a. https://www.gov.uk/government/publications/digital-regulation-driving-growth-and-unlocking-innovation/digital-regulation-driving-growth-and-unlocking-innovation

Department for Digital, Culture, Media & Sport. Government response to the consultation on the National Data Strategy; 2021b. https://www.gov.uk/government/consultations/uk-national-data-strategy-nds-consultation/outcome/government-response-to-the-consultation-on-the-national-data-strategy

Dobra, Z. and Dhir, K.S. (2020), "*Technology jump in the industry: human–robot cooperation in production*", Industrial Robot: The International Journal of Robotics Research and Application, Vol. 47 No. 5.

Eiris, R. and Gheisari, M. (2017), *"Research trends of virtual human applications in architecture, engineering and construction"*, Journal of Information Technology in Construction, Vol. 22, pp. 168-184.

European Commission. Horizon Europe: Strategic plan 2021–2024. Publications Office of the European Union; 2021b. https://data.europa.eu/doi/https://doi.org/10.2777/083753

European Commission. Proposal for a regulation laying down harmonised rules on artificial intelligence; 2021c. https://digital-strategy.ec.europa.eu/en/library/proposal-regulation-laying-down-harmonised-rules-artificial-intelligence

European Data Protection Board. European Data Protection Board—48th Plenary Session; 2021. https://edpb.europa.eu/news/news/2021/european-data-protection-board-48th-plenary-session_en

Everett, J. G. (1999). Overexertion injuries in construction. *Journal of construction engineering and management*, *125*(2), 109-114.

Ghaffar, S. H., Corker, J., & Fan, M. (2018). Additive manufacturing technology and its implementation in construction as an eco-innovative solution. *Automation in Construction*, *93*, 1-11.

Gharbia, M., Chang-Richards, A., Lu, Y., Zhong, R.Y. and Li, H. (2020), *"Robotic technologies for on-site building construction: a systematic review"*, Journal of Building Engineering, Vol. 32, p. 101584.

Golizadeh, H., Hosseini, M.R., Martek, I., Edwards, D., Gheisari, M., Banihashemi, S. and Z hang, J. (2019), *"Scientometric analysis of research on "remotely piloted aircraft": a research agenda for the construction industry"*, Engineering, Construction and Architectural Management, Vol. 27 No. 3, pp. 634-657.

Goodson M. The UK AI strategy: Are we listening to the experts?; 2021. https://datasciencesection.org/2021/09/13/the-uk-ai-strategy-are-we-listening-to-the-experts/

Government. UK (2019) What is the robots for a safer world challenge? https://www.gov.uk/government/collections/robots-for-a-safer-world-industrial-strategy-challenge-fund (Accessed 21 August 2021).

Green, S.A., Chen, X.Q., Billinghurst, M. and Chase, J.G. (2008), *"Human robot collaboration: an augmented reality approach, a literature review and* *analysis*", Proceedings of the ASME International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, DETC2007, pp. 117-126.

Gualtieri, L., Rauch, E. and Vidoni, R. (2021), "*Emerging research fields in safety and ergonomics in industrial collaborative robotics: a systematic literature review*", Robotics and Computer-Integrated Manufacturing, Vol. 67.

Hall, J., Gaved, M. and Sargent, J., (2021). Participatory research approaches in times of Covid-19: a narrative literature review. *International Journal of Qualitative Methods*, *20*, p.16094069211010087.

Hennig, M., Brandes, U., Pfeffer, J. and Mergel, I. (2012), "*Studying social networks: a guide to empirical research*", Campus Verlag, New York, NY.

Ilyas, M., Khaw, H.Y., Selvaraj, N.M., Jin, Y. and Zhao, X. (2021), "*Robot-assisted object detection for construction automation: data and information-driven approach*", IEEE/Asme Transactions on Mechatronics, Vol. 26, pp. 2845-2856.

Kale, S., & Arditi, D. (2010). Innovation diffusion modeling in the construction industry. *Journal of construction engineering and management*, *136*(3), 329-340.

Kamath, A. and Sharma, R.K. (2019), "*Robotics in construction: opportunities and challenges*", International Journal of Recent Technology and Engineering, Vol. 8, pp. 2227-2230.

Kas, K.A. and Johnson, G.K. (2020), "*Using unmanned aerial vehicles and robotics in hazardous locations safely*", Process Safety Progress, Vol. 39 No. 1, pp. 1-13.

Kasperzyk, C., Kim, M.K. and Brilakis, I. (2017), "*Automated re-prefabrication system for buildings using robotics*", Automation in Construction, Vol. 83, pp. 84-195.

Kazim E, Kerrigan C, Koshiyama A. EU proposed AI legal framework. SSRN Electron J. 2021. https://doi.org/10.2139/ssrn.3846898.

Kazim E, Koshiyama A. The interrelation between data and AI ethics in the context of impact assessments. AI and Ethics. 2021;1(3):219–25. https://doi.org/10.1007/s43681-020-00029-w.

Kazim E, Polle R, Carvalho G, Koshiyama A, Inness C, Knight A, Gorski C, Barber D, Lomas E, Yilmaz E, Thompson G, Ahamat G, Pavey G, Platts K, Szpruch L, Gregorovic M, Rodrigues

M, Ugwudike P, Nachev P, Goebel R. Towards AI standards: thought-leadership in AI legal, ethical and safety specifications through experimentation. SSRN Electron J. 2021. https://doi.org/10.2139/ssrn.3935987.

Kim, S., Moore, A., Srinivasan, D., Akanmu, A., Barr, A., Harris-Adamson, C., ... & Nussbaum, M. A. (2019). Potential of exoskeleton technologies to enhance safety, health, and performance in construction: Industry perspectives and future research directions. *IISE Transactions on Occupational Ergonomics and Human Factors*, *7*(3-4), 185-191.

Kim, T., Lee, D., Lim, H., Lee, U. and Cho, H. (2021), "*Exploring research trends and network characteristics in construction automation and robotics based on keyword network analysis*", Journal of Asian Architecture and Building Engineering, Vol. 20 No. 4, pp. 442-457.

Koshiyama A, Kazim E, Treleaven P, Rai P, Szpruch L, Pavey G, Ahamat G, Leutner F, Goebel R, Knight A, Adams J, Hitrova C, Barnett J, Nachev P, Barber D, Chamorro-Premuzic T, Klemmer K, Gregorovic M, Khan S, Lomas E. Towards algorithm auditing: a survey on managing legal, ethical and technological risks of AI, ML and associated algorithms. SSRN Electron J. 2021. https://doi.org/10.2139/ssrn.3778998.

Kunic, A., Naboni, R., Kramberger, A. and Schlette, C. (2021), "*Design and assembly automation of the robotic reversible timber beam*", Automation in Construction, Vol. 123.

Kurien, M., Kim, M.K., Kopsida, M. and Brilakis, I. (2018), "*Real-time simulation of construction workers using combined human body and hand tracking for robotic construction worker system*", Automation in Construction, Vol. 86, pp. 125-137.

Li, Y., & Liu, C. (2019). Applications of multirotor drone technologies in construction management. *International Journal of Construction Management*, *19*(5), 401-412.

Liang, C.J., Kamat, V.R. and Menassa, C.C. (2019), "*Teaching robots to perform construction tasks via learning from demonstration*", Proceedings of the 36th International Symposium on Automation and Robotics in Construction, ISARC 2019, pp. 1305-1311.

Linner, T., Pan, M., Pan, W., Taghavi, M., Pan, W., & Bock, T. (2018). Identification of usage scenarios for robotic exoskeletons in the context of the Hong Kong construction industry. In *Proceedings of the 35th International Symposium on Automation and Robotics in Construction (ISARC)* (pp. 40-47).

Linner, T., Pan, W., Hu, R., Zhao, C., Iturralde, K., Taghavi, M., & Bock, T. (2020). A technology management system for the development of single-task construction robots. *Construction Innovation*.

Linner, T., Pan, W., Hu, R., Zhao, C., Iturralde, K., Taghavi, M., Trummer, J., Schlandt, M. a nd Bock, T. (2020), "*A technology management system for the development of single-task construction robots*", Construction Innovation, Vol. 20 No. 1, pp. 96-111.

Liu, M., Fang, S., Dong, H. and Xu, C. (2021a), "*Review of digital twin about concepts, technologies, and industrial applications*", Journal of Manufacturing Systems, Vol. 58, pp. 346-361.

Lundeen, K.M., Kamat, V.R., Menassa, C.C. and McGee, W. (2017), "*Scene understanding for adaptive manipulation in robotized construction work*", Automation in Construction, Vol. 82, pp. 16-30.

Maarouf, H. (2019). Pragmatism as a supportive paradigm for the mixed research approach: Conceptualizing the ontological, epistemological, and axiological stances of pragmatism. *International Business Research*, *12*(9), pp.1-12.

Mahbub, R. (2008). *An investigation into the barriers to the implementation of automation and robotics technologies in the construction industry* (Doctoral dissertation, Queensland University of Technology).

Mahbub, R. (2015), "*Framework on the barriers to the implementation of automation and robotics in the construction industry*", International Journal of Innovation in Management, Vol. 3, No. 17.

Mariam, A.T., Olalusi, O.B. and Haupt, T.C. (2021), "*A scientometric review and meta-analysis of the health and safety of women in construction: structure and research trends*", Journal of Engineering, Design and Technology, Vol. 19 No. 2, pp. 446-466.

Martinez, J.G., Gheisari, M. and Alarcón, L.F. (2020), "*UAV integration in current construction safety planning and monitoring processes: case study of a high-rise building construction project in Chile*", Journal of Management in Engineering, Vol. 36 No. 3, p. 5020005.

McMeel, D. (2019), "*Robots and AR: towards a platform economy for construction*", Journal of Information Technology in Construction, Vol. 24, pp. 527-539.

Melenbrink, N., Rinderspacher, K., Menges, A. and Werfel, J. (2020), "*Autonomous anchoring for robotic construction*", Automation in Construction, Vol. 120, p. 103391.

Melnikovas, A., (2018). Towards an explicit research methodology: Adapting the research onion model for futures studies. *Journal of Futures Studies*, *23*(2), pp.29-44.

Nagatani, K., Abe, M., Osuka, K., Chun, P., Okatani, T., Nishio, M., Chikushi, S., Matsubara, T. and Ikemoto, Y. (2021), "*Innovative technologies for infrastructure construction and maintenance through collaborative robots based on an open design approach*", Advanced Robotics, Vol. 35 No. 11.

Ndlovu, T., Root, D., & Wembe, P. (2020). A review of the advantages and disadvantages of the use of automation and robotics in the construction industry. *The Construction Industry in the Fourth Industrial Revolution*, 197.

Newman, C., Edwards, D., Martek, I., Lai, J., Thwala, W. D., & Rillie, I. (2020). Industry 4.0 deployment in the construction industry: a bibliometric literature review and UK-based case study. *Smart and Sustainable Built Environment*.

Office for Artificial Intelligence. National AI strategy; 2021. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1020402/National_AI_Strategy_-_PDF_version.pdf

Ogunseiju, O., Olayiwola, J., Akanmu, A. and Olatunji, O.A. (2021), "*Evaluation of postural-assist exoskeleton for manual material handling*", Engineering Construction Architectural Management.

Oke, A.E. and Kineber, A.F. (2021), "*Modeling the robotics implementation barriers for construction projects in developing countries*", International Journal of Building Pathology and Adaptation.

Okpala, I., Nnaji, C., & Karakhan, A. A. (2020). Utilizing emerging technologies for construction safety risk mitigation. *Practice Periodical on Structural Design and Construction*, *25*(2), 04020002.

Olawumi, T.O., Chan, D.W.M. and Wong, J.K.W. (2017), "*Evolution in the intellectual structure of BIM research: a bibliometric analysis*", Journal of Civil Engineering and Management, Vol. 23 No. 8, pp. 1060-1081.

Opsahl, T., Agneessens, F. and Skvoretz, J. (2010), "*Node centrality in weighted networks: generalizing degree and shortest paths*", Social Networks, Vol. 32 No. 3, pp. 245-251, doi: 10.1016/j.socnet.2010.03.006.

P. Bishop, A. Hines, T. Collins (2007). The current state of scenario development: an overview of techniques Foresight, 9 (1), pp. 5-25.

Palikhe, S., Yirong, M., Choi, B. Y., & Lee, D. E. (2020). Analysis of Musculoskeletal Disorders and Muscle Stresses on Construction Workers' Awkward Postures Using Simulation. *Sustainability*, *12*(14), 5693.

Pan, M., Linner, T., Pan, W., Cheng, H. M., & Bock, T. (2020a). Influencing factors of the future utilisation of construction robots for buildings: A Hong Kong perspective. *Journal of Building Engineering*, *30*, 101220.

Pan, M., Linner, T., Pan, W., Cheng, H., & Bock, T. (2018). A framework of indicators for assessing construction automation and robotics in the sustainability context. *Journal of Cleaner Production*, *182*, 82-95.

Pan, M., Linner, T., Pan, W., Cheng, H., & Bock, T. (2020b). Structuring the context for construction robot development through an integrated scenario approach. *Automation in Construction*, *114*, 103174.

Pan, W., Chen, L., & Zhan, W. (2019). PESTEL analysis of construction productivity enhancement strategies: A case study of three economies. *Journal of Management in Engineering*, *35*(1), 05018013.

Pan, M., Linner, T., Pan, W., Cheng, H. and Bock, T. (2020), "*Structuring the context for construction robot development through integrated scenario approach*", Automation in Construction, Vol. 114.

Pan, M., Linner, T., Pan, W., Cheng, H. and Bock, T. (2020a), "*Influencing factors of the future utilisation of construction robots for buildings: a Hong Kong perspective*", Journal of Building Engineering, Vol. 30, p. 101220.

Pan, M., Linner, T., Pan, W., Cheng, H. and Bock, T. (2020b), "*Structuring the context for construction robot development through integrated scenario approach*", Automation in Construction, Vol. 114.

Park, Y.S., Konge, L. and Artino, A.R., (2020). The positivist paradigm of research. *Academic Medicine*, *95*(5), pp.690-694.

Parliament UK (2018), Automation and Industrial Strategy: UK as world leader. https://publications.parliament.uk/pa/cm201719/cmselect/cmbeis/1093/109307.htm (Accessed 30 August 2021)

Perez, J.A., Deligianni, F., Ravi, D. and Yang, G.Z. (2018), "*Artificial intelligence and robotics*", UK-RAS Network Robotics and Autonomous Systems.

Pricewaterhouse Coopers (2021). Will robots steal our jobs? An international analysis of the long-term impact of automation. https://www.pwc.co.nz/pdfs/2018pdfs/impact-of-automation-on-jobs-Feb-2018.pdf (Accessed 29 August 2021)

Prime Minister's Office. Prime Minister sets out plans to realise and maximise the opportunities of scientific and technological breakthroughs [Press Release]; 2021. https://www.gov.uk/government/news/prime-minister-sets-out-plans-to-realise-and-maximise-the-opportunities-of-scientific-and-technological-breakthroughs

Rakha, T., & Gorodetsky, A. (2018). Review of Unmanned Aerial System (UAS) applications in the built environment: Towards automated building inspection procedures using drones. *Automation in Construction*, *93*, 252-264.

Ramirez, R., Mukherjee, M., Vezzoli, S., & Kramer, A. M. (2015). Scenarios as a scholarly methodology to produce "interesting research". *Futures*, *71*, 70-87.

Reinhardt, D., Haeusler, M.H., London, K., Loke, L., Feng, Y., Barata, E.D.O., Firth, C., Dunn , K., Khean, N., Fabbri, A., Connor, D.W. and Masuda, R. (2020), "*CoBuilt 4. 0: investigating the potential of collaborative robotics for subject matter experts*", International Journal of Architectural Computing, Vol. 18 No. 4.

Ryu, J., Mcfarland, T., Banting, B., Haas, C.T. and Abdel-Rahman, E. (2020), "*Health and productivity impact of semi-automated work systems in construction*", Automation in Construction, Vol. 120, p. 103396.

Sahay, A. (2016). Peeling Saunders' research onion. *Research Gate, Art*, pp.1-5.

Saidi, K. S., Bock, T., & Georgoulas, C. (2016). Robotics in construction. In *Springer handbook of robotics* (pp. 1493-1520). Springer, Cham.

Saka, A.B. and Chan, D.W.M. (2019a), "*A global taxonomic review and analysis of the development of BIM research between 2006 and 2017*", Construction Innovation, Vol. 19 No. 3, pp. 465-490.

Saka, A.B. and Chan, D.W.M. (2019b), "*A scientometric review and metasynthesis of building information modelling (BIM) research in Africa*", Buildings, Vol. 9 No. 21.

Salmi, T., Ahola, J.M., Heikkilä, T., Kilpeläinen, P. and Malm, T. (2018), "*Human-robot collaboration and sensor-based robots in industrial applications and construction*", Robotic Building, Springer Series in Adaptive Environments, Springer International Publishing AG, part of Springer Nature 2018, p. 25.

Schneider, S. P. (2001). Musculoskeletal injuries in construction: a review of the literature. *Applied occupational and environmental hygiene*, *16*(11), 1056-1064.

Sellner, B., Heger, F.W., Hiatt, L.M., Simmons, R. and Singh, S. (2006), "*Coordinated multiagent teams and sliding autonomy for large-scale assembly*", Proceedings of the IEEE, Vol. 94 No. 7, pp. 1425-1443.

Seo, J., Lee, S., Kim, J. and Kim, S. (2011), "*Task planner design for an automated excavation system*", Automation in Construction, Vol. 20 No. 7, pp. 954-966.

Su, H. and Lee, P.C. (2010), "*Mapping knowledge structure by keyword co-occurrence: a first look at journal papers in technology foresight*", Scientometrics, Vol. 85 No. 1, pp. 65-79.

Tankova, T., & da Silva, L. S. (2020). Robotics and Additive Manufacturing in the Construction Industry. *Current Robotics Reports*, *1*(1), 13-18.

Tavares, P., Costa, C.M., Rocha, L., Malaca, P., Costa, P., Moreira, A.P., Sousa, A. and Veiga , G. (2019), "*Collaborative welding system using BIM for robotic reprogramming and spatial augmented reality*", Automation in Construction, Vol. 106, p. 102825.

Tsuruta, T., Miura, K. and Miyaguchi, M. (2019), "*Mobile robot for marking free access floors at construction sites*", Automation in Construction, Vol. 107, p. 102912.

Wagner, H.J., Alvarez, M., Kyjanek, O., Bhiri, Z., Buck, M. and Menges, A. (2020), "*Flexible and transportable robotic timber construction platform – TIM*", Automation in Construction, Vol. 120, p. 103400.

Wang, D., Zheng, L., Yu, H., Zhou, W. and Shao, L. (2016), "*Robotic excavator motion control using a nonlinear proportional-integral controller and cross-coupled pre-compensation*", Automation in Construction, Vol. 64, pp. 1-6.

Wang, X. and Zhu, Z. (2021), "*Vision – based framework for automatic interpretation of construction workers ' hand gestures*", Automation in Construction, Vol. 130, p. 103872.

Wang, X., Liang, C.J., Menassa, C.C. and Kamat, V.R. (2021), "*Interactive and immersive process-level digital twin for collaborative human – robot construction work*", Journal of Computing in Civil Engineering, Vol. 35 No. 6, pp. 1-19.

Wen, J. and Gheisari, M. (2020), "*Using virtual reality to facilitate communication in the AEC domain: a systematic review*", Construction Innovation, Vol. 20 No. 3.

Wolf, F. (2020), Human-Robot Teams: A Review, SpringerLink, Springer.

Wolf, F.D. and Stock-Homburg, R. (2020), "*Human-robot teams: a review. in Lecture notes in computer science (including subseries lecture notes in artificial intelligence and lecture notes in bioinformatics)*", Springer Science and Business Media Deutschland GmbH, pp. 246-258.

Xiang, S., Wang, R. and Feng, C. (2019), "*Towards mobile projective AR for construction co-robots*", Proceedings of the 36th International Symposium on Automation and Robotics in Construction, ISARC 2019, pp. 1106-1113.

Xiang, S., Wang, R. and Feng, C. (2021), "*Mobile projective augmented reality for collaborative robots in construction*", Automation in Construction, Vol. 127.

Zavadskas, E. K. (2010). Automation and robotics in construction: International research and achievements. *Automation in construction*, *19*(3), 286-290.

Zhang, T., Zhang, W. and Gupta, M.M. (2017), "*Resilient robots: concept, review, and future directions*", Robotics, Vol. 6 No. 4, pp. 1-14.

Zheng, Y., Tetik, M., Törmä, S., Peltokorpi, A., & Seppänen, O. (2020). A Shared Ontology for Logistics Information Management in the Construction Industry. In *ISARC. Proceedings of the International Symposium on Automation and Robotics in Construction* (Vol. 37, pp. 1278-1285). IAARC Publications.

Zhou, Z., Goh, Y. M., & Li, Q. (2015). Overview and analysis of safety management studies in the construction industry. *Safety science*, *72*, 337-350.

Zhou, S. and Gheisari, M. (2018), "*Unmanned Aerial System Applications in construction: a systematic review*", Construction Innovation, Vol. 18 No. 4, pp. 453-468.

Zhou, Y., Guo, H., Ma, L., Zhang, Z. and Skitmore, M. (2021), "*Image-based onsite object recognition for automatic crane lifting tasks*", Automation in Construction, Vol. 123, p. 103527.

Zhu, Q., Du, J., Shi, Y. and Wei, P. (2021), “*Neurobehavioral assessment of force feedback simulation in industrial robotic teleoperation*”, Automation in Construction, Vol. 126, p. 103674.

Zieba, S., Polet, P., Vanderhaegen, F. and Debernard, S. (2009), “*Resilience of a human-robot system using adjustable autonomy and human-robot collaborative control*”, International Journal of Adaptive and Innovative Systems, Vol. 1 No. 1

Taillon, L. et al., 2009. Quantifying the waste reduction potential of using prefabrication in building construction in Hong Kong. Waste Management.

Tam, V.W.Y. et al., 2007. Towards the adoption of prefabrication in construction. Building and Environment.

Jung, K. et al., 2013. Robot-based construction automation: An application to steel beam assembly (Part II). Automation in Construction.

Gambao, E. et al., 2000. Robot assembly system for computer-integrated construction. Automation in Construction.

Khoshnevis, B., 2004. Automated construction by contour crafting – related robotics and information technologies. Automation in Construction.

Choi, H.S. et al., 2005. Development of a hybrid robot for construction works with pneumatic actuator. Automation in Construction.

Chu, B. et al., 2013. Robot-based construction automation: An application to steel beam assembly (Part I). Automation in Construction.

Wilson, R.H. et al., 1994. Geometric Reasoning About Mechanical Assembly. Artificial Intelligence.

Sparkman, G. et al. Standardization and preassembly: Adding value to construction projects.

Schoenborn, J.M., A case study approach to identifying the constraints and barriers to design innovation for modular construction, Master of Science Thesis in Architecture, Faculty of the Virginia Polytechnic Institute and State University.

Sacks, R. et al., 2004. Process model perspectives on management and engineering procedures in the precast/prestressed concrete industry. Journal of Construction Engineering and Management, ASCE.

Wright, E., Fast build nation: Richard Ogden on offsite construction.

Steinhardt, D.A. et al., Reshaping Housing – The role of prefabricated systems.

Balaguer, C. & Abderrahim, M., Trends in Robotics and Automation in Construction.

Bock, T., Construction Automation and Robotics.

Ibbs, W., 2012. Construction Change: Likelihood, Severity, and Impact on Productivity. Journal of Legal Affairs and Dispute Resolution in Engineering and Construction.

Kibert, C., 2016. Sustainable Construction: Green Building Design and Delivery.

Dubois, A. et al., 2002. The construction industry as a loosely coupled system: implications for productivity and innovation. Construction Management and Economics.

Low, S.P. et al., 1999. The application of JIT philosophy to construction: a case study in site layout. Construction Management and Economics.

Gann, D., 1996. Construction as a manufacturing process? Similarities and differences between industrialized housing and car production in Japan. Construction Management and Economics.

Skibniewski, M.J., 1988. Robotics in civil engineering

AbdulKadir, G., & Godfaurd, J. (2015). "Integrating Building Information and Health and Safety for Onsite Construction." Health Saf. Work, 6, 39-45.

Ahsan, S., El-Hamalawi, A., Bouchlaghem, D., & Ahmad, S. (2007). "Mobile Technologies for Improved Collaboration on Construction Sites." Architectural Engineering and Design Management, 3, 257–272.

Azhar, S., Bahringer, A., Khalfan, M., Sattineni, A., & Maqsood, T. (2012). "BIM for Facilitating Construction Safety Planning and Management at Jobsite." Proceedings of the CIB W099 International Conference on Modelling and Building Health and Safety, 82-92.

Azmy, N., & Zain, A. (2016). "The Applications of Technology in Enhancing Safety and Health Aspects on Malaysian Construction Projects." ARPN Journal of Engineering and Applied Sciences, 11, 7209–7213.

Balaguer, C., & Abderrahim, M. (2008). Trends in Robotics and Automation in Construction. Intechopen.

Bansal, V. K. (2011). "Application of geographic information systems in construction safety planning." International Journal of Project Management, 29, 66-77.

Bock, T., Linner, T., & Ikeda, W. (2012). Exoskeleton and Humanoid Robotic Technology in Construction and Built Environment. Intechopen.

Bouchlaghem, D., Shang, H., Whyte, J., & Ganah, A. (2005). "Visualisation in architecture, Engineering and construction (AEC)." Automation in Construction, 14(3), 287–295.

Brilakis, I. (2006). "Remote Wireless Communications for Construction Management: A Case Study." Joint International Conference on Computing and Decision Making in Civil and Building Engineering, 135-144.

Brilakis, I. (2007). "Long-distance wireless networking for site–office data communications." ITCon, 12, 151–164.

Chae, S. (2009). "Development of Warning System for Preventing Collision Accident on Construction Site." 26th International Symposium on Automation and Robotics in Construction.

Cheung, S. O., Cheung, K. K. W., & Seun, H. C. H. (2004). "CSHM: Web-based safety and health monitoring system for construction management." Journal of Safety Research, 35(2), 159–170.

Chu, B. (2013). "Robot-based construction automation: an application to steel beam assembly." Autom. Constr., 32, 46–61.

Dodge Data and Analytics. (2017). Safety Management in the Construction Industry, Smart Market Report, Bedford, MA.

Druley, K., Musick, T., & Trotto, S. (2016). "Researcher Explores how to make temporary structures on a construction site safe." Safety and Health, 193.

Dude. (2014). Fortis Exoskeleton. Retrieved from http://www.dudeiwantthat.com/fitness/equipment/fortis-exoskeleton.asp

Dupre, D. (2001). Accidents at work in the EU 1998-1999, KS-NK-01-016-EN-I, Eurostat, Luxembourg.

Eastman, C., Teicholz, P., Sacks, R., & Liston, K. (2011). BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers and Contractors, 2nd ed. John Wiley and Sons, NY.

Frane, D. (2016). "7 Cool and Unusual Tools from the 2016 STAFDA Show." Retrieved from http://www.toolsofthetrade.net/power-tools/7-cool-and-unusual-tools-from-the-2016-stafda-show_o

Ganah, A., & John, G. A. (2015). "Integrating building information modelling and health and safety for onsite construction." Safety and Health at Work, 6, 39-45.

Hinze, J., & Teizer, J. (2011). "Visibility-related fatalities related to construction equipment." Safety Science, 49, 709-718.

Hu, Z., Zhang, J., & Lu, X. (2010). "Development of a sub-building information model for 4D structural safety analysis during construction." Proceedings of the International Conference on Computing in Civil and Building Engineering (ICCCBE 2010), Nottingham, UK.

Jung, K., Chu, B., & Hong. (2013). "Robot-based construction automation: An application to steel beam assembly (part II)." Automation in Construction, 32, 62–79.

Kim, H., & Ahn, H. (2011). "Temporary facility planning of a construction project using BIM (Building Information Modeling)." Proceedings of the 2011 ASCE International Workshop on Computing in Civil Engineering, Miami, FL.

Kim, D. I., & Cho, H. (2010). "Safety and productivity analysis on alternative steel column-girder joint for automated construction." Proceedings of International Conference on Control, Automation and Systems (ICCAS 2010), Seoul, pp. 2338–41.

Ku, K., & Mills, T. (2010). "Research Needs for Building Information Modelling for Construction Safety." International Proceedings of Associated Schools of Construction 45th Annual Conference, Boston, MA.

Kyodo. (2015). Panasonic will sell robot suits starting in September. Retrieved from http://www.japantimes.co.jp/news/2015/07/03/business

Appendix 1: Questionnaire

Dear participant,

Thank you for volunteering to complete this survey. Your response is important for the completion of my research. I am a PhD candidate researching 'Robotic technology adoption in preventing construction injuries in the United Kingdom'. The research seeks to investigate the uptake, applicability, and challenges in adopting robotic technology in preventing injuries and fatalities in the construction sector. The responses you provide are therefore important. It would, however, be completely confidential, anonymised, and would be used strictly for this research and not for commercial uses or third parties. Your responses will therefore be greatly appreciated. You have the right to opt out at any stage of the survey, as your participation is completely voluntary.

Do you mind taking some time to look through and provide answers to the questions below – this would only take less than 10-15 minutes of your time. Once the data have been collected, they would be collated and analysed and would be used to support the research findings and make useful recommendations.

If you have any questions about this research, please feel free to contact me directly. You can reach me at i.o.obaigwe@edu.salford.ac.uk. For more information, please contact my thesis supervisor, Professor Zeeshan Aziz.

PART 1: Demographics (Please tick as appropriate)

1. **Years of Experience in the construction industry**

Below 5 years
6-15 years
16-25 years
More than 25 years

Education level

No formal education
High school
Diploma/Certificates
Bachelors
Master's Degree
Others (please specify)

Years of Experience

Part 2: Please provide an answer that most appropriately answers the questions below.

In your assessment, what is the level of effective usage of robotic technologies, i.e exoskeleton arm, where present, in construction activities?

High	
Medium	
Low	
Not sure	

To what extent can robotic technologies be used to prevent common construction-related injuries, near misses, and fatalities?

High	
Medium	
Low	
Not sure	

In your assessment and response to the question above, what is your perception of the transition to robots for performing construction activities in the UK?

Positive	
Negative	
Neutral	
Not sure	

What is your assessment of the level of preparedness and readiness of the UK construction industry for the adoption of robotic technologies?

High	
Medium	
Low	
Not sure	

In your assessment, to what extent do existing laws and regulations moderating the use of Artificial Intelligence and robotic technologies encourage its adoption in the construction industry in the UK?

High	
Medium	
Low	
Not sure	

In your assessment, how significant are the organisational and institutional barriers for the adoption of robotic technologies in the construction sector?

High	

Medium	
Low	
Not sure	

Does the potential blowback effect for the adoption of these technologies prevent their uptake?
In your opinion, do you think that the UK construction sector is ripe for the uptake of robotic technologies?

High	
Medium	
Low	
Not sure	

PART 3: Limitations to robotic technology adoption in the UK construction industry

Factors	SA	A	N	D	SD
Intellectual property issues about existing standards in the UK construction industry limit the uptake of robotic technologies.					
Institutional barriers relating to the technology transition for robotics to replace workers affect the uptake in the construction industry.					
Funding, research, and development indigenous to the UK a significant factors affecting its adoption.					
The level of uptake is associated with the initial higher level of acquiring robotic technologies.					
Supply chain issues and construction site analytics are critical factors affecting robotic technologies in the UK.					

PART 4: Challenges of robotic technology uptake in the UK

Factors	SA	A	N	D	SD
The cost implication for adopting, developing, and operationalising its use affects its use in the UK construction sector.					
Limited usage for all aspects of construction works affects its operability in all aspects of construction.					
Disruptive effects on traditional construction activities limit its use.					
Technicalities and requisite skills required to operate robots by construction workers limit their use.					
The desire to use robots in construction by key construction stakeholders has a deterministic role in its uptake.					
Technical knowledge is required to implement its use in the construction industry.					

What recommendations would you suggest to drive the uptake of robotic technologies in the UK construction sector?
………
………
………………………………………………………………………

What additional comments can you provide that explain the main challenges facing robotic technologies adoption for the prevention of construction injuries in the UK
………
………
………………………………………………………………

Thank you for your time.

Appendix II: Interview Questions

University of Salford MANCHESTER

Dear participant,

Thank you for volunteering to be part of this interview. Your response is important for the completion of my research. I am a PhD candidate researching 'Robotic technology adoption in preventing construction injuries in the United Kingdom'. The research seeks to investigate the uptake, applicability, and challenges in the adoption of robotic technology in preventing injuries and fatalities in the construction sector. The responses you provide are therefore important. It would, however, be completely confidential, anonymised, and would be used strictly for this research and not for commercial uses or third parties. Your responses will therefore be greatly appreciated. You have the right to opt out at any stage of the survey, as your participation is completely voluntary.

Do you mind taking some time to look through and provide answers to the questions below – this would only take less than 10-15 minutes of your time.

Do you consent that your responses be recorded for this research?

Once the data have been collected, they would be collated and analysed and would be used to support the research findings and make useful recommendations.

Interview Questions

1. Tell us about yourself. Brief introduction
2. How long have you been working in the construction industry? What is your role in the construction industry?
3. Does your organisation adopt or deploy robotics in the construction site? If yes, could you speak about the types and what uses
4. What are the biggest opportunities for the use of robotics in your construction site?
5. Have you encountered any barriers with the way robotics has been deployed in your construction site?
6. What are the barriers preventing the uptake of robotics in the construction industry in the UK?
7. How is robotics preventing construction-related safety hazards that the average construction worker are exposed to considering that construction is high-risk laden.
8. Do you foresee greater collaboration between humans and robots in the construction industry?
9. Is the UK construction industry advancing towards increased robotisation, or is this a distant reality for the construction industry?
10. In what ways will robotic technology impact the construction industry in the UK?

Appendix III: Interview outreach

My name is Innocent Onyeka Obiaigwe, a PhD student in Construction and Project Management at the University of Salford, Greater Manchester, United Kingdom.

I am reaching out regarding a new research study I am conducting relating to ‘Robotic technology adoption in the prevention of construction injuries in the United Kingdom’. The research seeks to investigate the uptake, applicability, and challenges in the adoption of robotic technology in preventing injuries and fatalities in the construction industry in the UK.

As part of this research, we’re conducting interviews with employers and thought leaders like yourself to better understand the barriers and prospects for robotic adoption in the construction industry in the UK. The interviews are entirely anonymous and take approximately 30 to 45 minutes. They are normally conducted virtually.

The study recognizes the critical role robotic technology plays in the construction ecosystem and seeks to explore how this can be adapted and adopted in the UK, as evident in comparable jurisdictions. I would value your time and insights as we conduct this research.

Would you be interested in participating in an interview for the project? If so, please let me know and we can find a time to connect in the next few weeks.

I’m happy to answer any questions you may have.

Thank you for your consideration,

Appendix IV: Demographics:

Table 8: Demographic Profile of Respondents

Category	**Sub-category**	**Percentage (%)**
Years of Experience	Less than 5 years	23%
	6 to 15 years	47%
	16 to 25 years	19%
	More than 25 years	11%
Professional Background	Engineer	11%
	Core construction role	20%
Educational Level	Diploma or equivalent certificate	11%
	Bachelor's degree	59%
	Master's degree or postgraduate	20%
	Other qualifications	10%
Organization Size	Small (5–25 employees)	27%
	Medium (26–100 employees)	54%
	Large (100+ employees)	19%